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# ACCESS TO SPACE STUDY

## Summary Report

Office of Space Systems Development  
NASA Headquarters

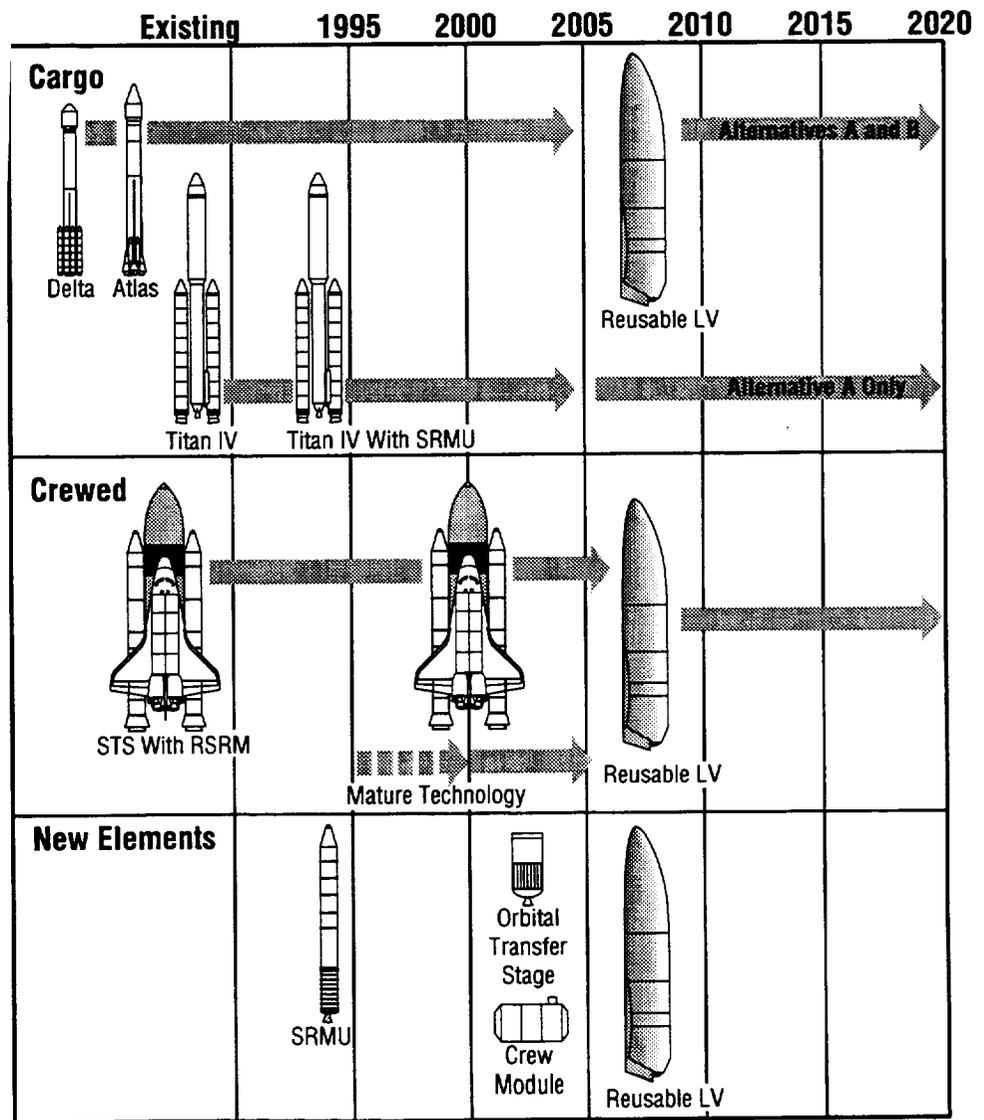
January 1994

N94-27151

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(NASA-TM-109693) ACCESS TO SPACE STUDY Summary Report (NASA) 78 p



National Aeronautics and Space Administration



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Office of Space Systems Development  
NASA Headquarters

January 1994



National Aeronautics and  
Space Administration

**Headquarters**

Washington, DC 20546-0001



Reply to Attn of: D

JAN 27 1994

TO: A/Administrator

FROM: D/Associate Administrator for Space Systems Development

SUBJECT: Access to Space Study

Enclosed is the final report on the Access to Space Study which was conducted during 1993.

It was my pleasure to lead the Study Team that enthusiastically accepted your charter to identify and assess the major alternatives for a long-range direction for space transportation that would support all U.S. needs (civilian, commercial, and national security) for several decades into the future.

The Study is also responsive to Congressional direction in the Fiscal Year 1993 VA-HUD-Independent Agencies Appropriations Bill to "... assess National launch requirements, potential alternatives and strategies to address such needs ... to permit formulation of multiyear program plans."

This Study is very timely. While its conclusions and recommendations are based upon the ground rules and criteria selected at the time, it will provide valuable input to the decisions that the Administration intends to make this year on U.S. launch strategy. It also establishes a strong basis for NASA participation in the ongoing OSTP Space Transportation Working Group and the DOD Launch Modernization Study.

A handwritten signature in black ink, appearing to read "Arnold D. Aldrich", written over a printed name.

Arnold D. Aldrich

Enclosure



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# ACCESS TO SPACE STUDY

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## Synopsis

This study was undertaken in response to a Congressional request in the NASA FY1993 Appropriations Act. The request coincided with an on-going internal NASA broad reassessment of the Agency's programs, goals, and long-range plans. Additional motivations for the study included a recognition that while today's space transportation systems meet current functional needs, they are costly and less reliable than desired, and lack desired operability. This has resulted in increased costs to the government and in severe erosion of the ability of U.S. industry to compete in the international space launch market. A further motivation is the past failure of the Administration and Congress to reach consensus on developing more efficient new launch systems.

This report summarizes the results of a comprehensive NASA in-house study to identify and assess alternate approaches to access to space through the year 2030, and to select and recommend a preferred course of action.

The goals of the study were to identify the best vehicles and transportation architectures to make major reductions in the cost of space transportation (at least 50 percent), while at the same time increasing safety for flight crews by at least an order of magnitude. In addition, vehicle reliability was to exceed 0.98 percent, and, as important, the robustness, pad time, turnaround time, and other aspects of operability were to be vastly improved.

This study examined three major optional architectures: (1) retain and upgrade the Space Shuttle and expendable launch vehicles, (2) develop new expendable vehicles using conventional technologies and transition from current vehicles beginning in 2005, and (3) develop new reusable vehicles using advanced technology, and transition from current vehicles beginning in 2008. The launch needs mission model utilized for the study was based upon today's projection of civil, defense, and commercial mission payload requirements.

Each of the three options resulted in a number of alternative architectures, any of which could satisfy the mission model needs. After comparing designs and capabilities of the alternatives within each of the three options, all defined to an equivalent depth using the same ground rules, a preferred architectural alternative was selected to represent each option. These were then compared and assessed as to cost, safety, reliability, environmental impact, and other factors.

The study concluded that the most beneficial option is to develop and deploy a fully reusable single-stage-to-orbit (SSTO) pure-rocket launch vehicle fleet incorporating advanced technologies, and to phase out current systems beginning in the 2008 time period. While requiring a large up-front investment, this new launch system is forecast to eventually reduce launch costs to the U.S. Government by up to 80 percent while increasing vehicle reliability and safety by about an order of magnitude. In addition, it would place the U.S. in an extremely advantageous position with respect to international competition, and would leapfrog the U.S. into a next-generation launch capability.

The study determined that while the goal of achieving single-stage-to-orbit fully reusable rocket launch vehicles has existed for a long time, recent advances in technology make such a vehicle feasible and practical in the near term provided that necessary technologies are matured and demonstrated prior to start of vehicle development.

Major changes in acquisition and operations practices, as well as culture, are identified as necessary in order to realize these economies. The study further recognized that the confident development of such a new launch vehicle can only be undertaken after the required technology is in hand. Therefore, the study recommended that a technology maturation and demonstration program be undertaken as a first step. Such a program would require a relatively modest investment for several years.

The study thus recommended that the development of an advanced technology single-stage-to-orbit rocket vehicle become a NASA goal, and that a focused technology maturation and demonstration be undertaken. Adoption of this recommendation could place the U.S. on a path to recapture world leadership in the international satellite launch marketplace, as well as enable much less costly and more reliable future government space activities.

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# Table of Contents

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Introduction .....	1
Purpose .....	2
Approach, Ground Rules, and Organization .....	3
Description of the Option Teams' Analyses .....	8
Option Team Down-Selects .....	59
New Operations Concept .....	61
Comparative Analysis .....	62
Observations and Conclusions .....	69
Recommendations .....	72



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# Introduction

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The 1993 NASA Appropriations Act included language that expressed Congress' concern about the rising costs of the Space Station and space transportation, and the likelihood that NASA's program budgets would, at best, be limited in the future. In view of these trends, the Congress' concerns focused on NASA's ability to field a viable space program. Congress requested that a study be performed to recommend improvements in Space Station *Freedom* and space transportation, and to examine and revalidate civilian and defense requirements for space launch. This study was to be done in close cooperation with other agencies.

At about the same time, NASA independently undertook a series of internal studies as part of a reassessment of the Agency's programs, goals, posture, and long-range plans. These studies considered various options for the redesign of Space Station *Freedom*, Space Shuttle safety and reliability improvements, alternative transportation systems, and others. Since the Space Station Redesign Study developed into a full-fledged program reorientation activity during 1993, space transportation emerged as the key remaining area of focus, being at the heart of NASA's ability to support a wide range of national objectives and continue a visionary civil space program.

Another major factor for this study's focus was that NASA, together with the Department of Defense (DOD) and the aerospace industry, had spent nearly a decade defining and advocating a new launch vehicle program (which culminated in the proposed National Launch System), without being able to reach consensus with the Congress that it should be developed.

Yet another factor was the continued erosion of the international market share for U.S. launch vehicles. This market share has dropped from 100 percent to about 30 percent, largely due to the development and fielding of the French-built Ariane system, which targeted and captured at least 50 percent of the world's space launch market. U.S. industry has found itself increasingly unable to effectively compete using the current generation of launch vehicles.

As a result of all these factors and trends, as well as the specific Congressional request, a comprehensive in-house study was undertaken by NASA to identify and assess the major alternatives for a long-range direction for space transportation. The scope of the study was to support all U.S. needs for space transportation—including civilian, commercial, and defense needs—for several decades into the future. This is the Access to Space Study, which was recently completed and is summarized herein.

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# Purpose

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The U.S. space transportation architecture meets the current needs for access to space. The Space Shuttle is the world's most reliable launch system, and also functions as a human-tended research laboratory and satellite deployment, retrieval, and repair facility. The expendable launch vehicle fleet and related upper stages can lift all required defense and commercial spacecraft to their required destinations.

While these systems are by no means dysfunctional, they have major shortcomings that will only increase in significance in the future, and thus are principal drivers for seeking major improvements in space transportation. While the launch vehicles differ in their particular characteristics, their aggregate shortcomings are well known. They are too costly, insufficiently reliable and safe, insufficiently operable, and increasingly losing market share to international competition.

This study focused on identifying long-term improvements leading to a space transportation architecture that would reduce the annual cost of space launch to the U.S. Government by at least 50 percent, increase the safety of flight crews by an order of magnitude, and make major improvements in overall system operability (turnaround time, schedule dependability, robustness, pad time, and so forth). The study horizon was set at the year 2030 in order to allow time for new vehicles using advanced technology to fairly demonstrate their potential.

Using these criteria, this study identifies options for a long-term direction for the U.S. to meet government, defense, and commercial needs for space transportation, together with long-range program plans for implementation. While the focus of the study is long term, it recognizes that immediate improvements are needed. Therefore, program recommendations identifying realistic near-term activities for transitioning to the long-term capability are also included.

# Approach, Ground Rules, and Organization

## Approach

The Access to Space Study team began by recognizing that the Space Shuttle and the expendable launch vehicle fleet represent a very large investment both in vehicles and their supporting infrastructure. It recognized, based on many past studies, that the replacement of the current capability with any new vehicle or vehicles designed to overcome the above-named shortcomings is likely to be an expensive and lengthy process.

Thus, the study approach considered, in parallel, a number of alternative approaches that differ in the degree of replacement of current capability, in the pace at which current systems are phased over to the new, and in the degree of utilization of new technologies. Three major alternative options were defined:

1. Provide necessary upgrades to continue primary reliance on the Space Shuttle and the current expendable launch vehicle (ELV) fleet through 2030.
2. Develop a new expendable launch system utilizing today's state-of-the-art technology, and transition from the Space Shuttle and today's expendable launch vehicles starting in 2005.
3. Develop a new reusable advanced technology next-generation launch system, and transition from the Space Shuttle and today's expendable launch vehicles starting in 2008.

This strategy and approach is illustrated in figure 1.

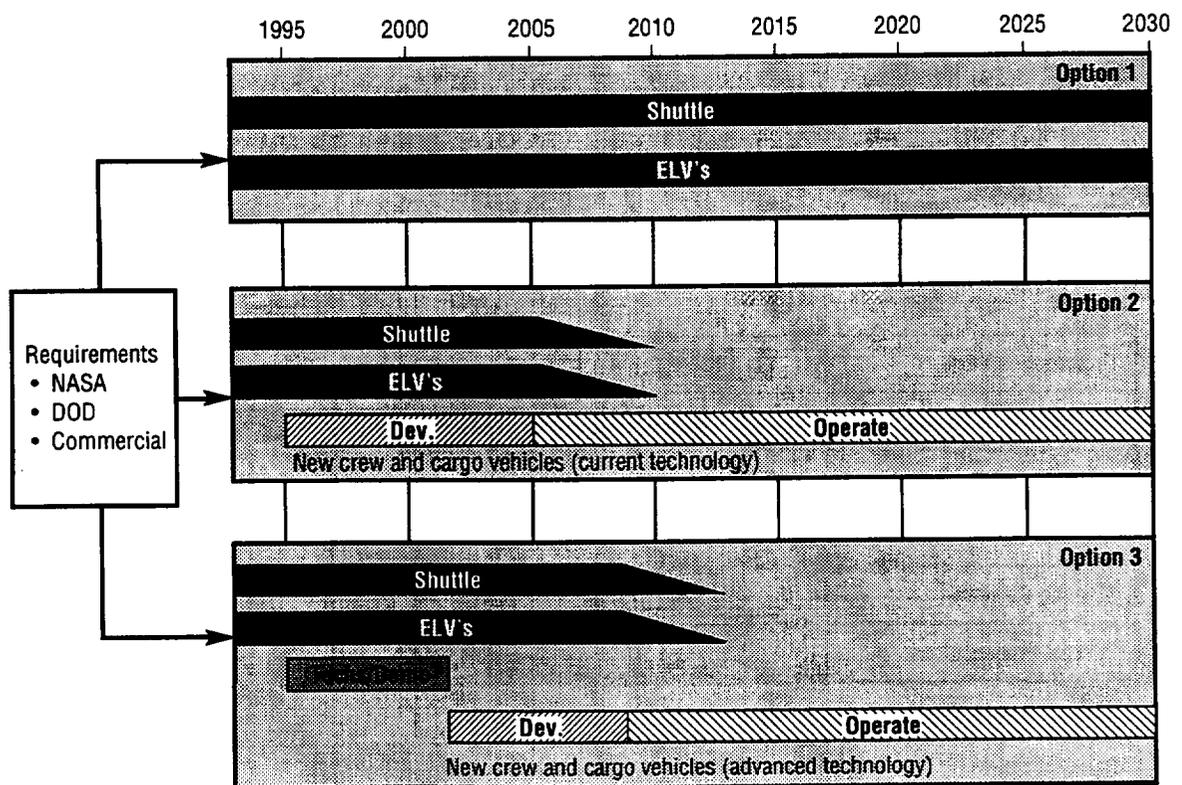


FIGURE 1.—Study strategy and approach.

Each of the options was to treat the entire architecture of launch vehicles required. Each would be analyzed by a separate study team working independently of the others. The recommendations of these teams would be assessed by a small group reporting to the study director.

Common goals were established, and evaluation criteria were developed based on the goals against which each of the options could be measured. These included performance and cost goals, operability, growth potential, environmental suitability, and others, as are shown in figure 2. These were organized into three categories in order of priority to facilitate both design selections and eventual comparative evaluation of the recommended architectures.

Fundamental Requirement	Essential Characteristics	Desired Features
1.1 Satisfy the national launch needs <ul style="list-style-type: none"> <li>• NASA crewed</li> <li>• NASA uncrewed</li> <li>• DOD</li> <li>• Commercial</li> </ul> (This includes definition of payloads from small to Shuttle/Titan class, and destinations at all altitudes and inclinations, as well as planetary.)	2.1 Improve crew safety by an order of magnitude (crew survivability >0.999). 2.2 Acceptable life-cycle costs, to include: A. Affordable DDT&E B. Improved operability and annual operating cost reduction over current systems (for STS equivalent <50 percent). Exclude costs of commercial flights. 2.3 Vehicle reliability of at least 0.98. 2.4 Environmentally acceptable: meet all environmental requirements planned for the year 2002.	3.1 Improve commercial competitiveness of launch vehicles. 3.2 Contribute to industrial economy (dual-use technology and processes). 3.3 Enable incremental development or improvements. 3.4 Improve capability relative to current systems (including STS).

DDT&E—Design, development, test, and evaluation                      STS—Space Transportation System

FIGURE 2.—Access to Space capability goals.

The most beneficial designs that survived elimination within each of the three option teams were to be assessed against these criteria, and a preferred architecture was to be selected from them. An implementation plan and recommended actions were to be the final output of the study. The overall schedule of the study is shown in figure 3.

Activities	1993										
	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.
Kickoff	▲					AIA—Aerospace Industries Association OMB—Office of Management and Budget OSTP—Office of Science and Technology Policy					
Organization/Plan	■										
Option Studies by Teams		■									
Interim Report			▲								
Assessment								■			
Steering Reviews		▲	▲		▲	▲	▲	▲	▲		
Internal Presentations								Administrator ▲		OMB/OSTP ▲	
External Presentations				AIA ▲							Congress ▲
Documentation									■		

FIGURE 3.—Access to Space Study schedule.

## Ground Rules

A number of ground rules were established for the Access to Space Study. Since a Space Station redesign was in progress, the Space Station *Freedom* design was utilized, but placed into the Mir orbit of 220 nautical miles (nmi) circular altitude at 51.6 degrees inclination. This was done to represent a worst-case scenario for the space transportation systems' requirements.

A common mission model was defined that included all U.S. defense, civilian, and commercial user elements covering the period from 1995 through 2030. This model was based on conservative extrapolation of current requirements and planned programs, and did not include major future possibilities such as exploration missions to the Moon and Mars. This mission model is shown in figure 4.

Vehicle Class	NASA	Commercial	DOD
Pegasus/Taurus Class	2.0	1 Nominal + 7 Growth	2
Delta Class	3.0	1 Nominal + 2 Growth	6
Atlas Class	2.0	3 Nominal + 0 Growth	3
Titan Class	0.3	—	3
Shuttle Class	8.0	—	—
Total Launches	15.3	5 Nominal + 9 Growth	14

FIGURE 4.—Annual launch demand mission model from 1995 to 2030.

For lack of solid forecasts of future traffic, the model was assumed to be constant through 2030. It was recognized that such a flat model was unlikely to endure over the long term and that excursions would eventually have to be treated as better models became available, as human exploration or other ambitious missions became better focused, or, hopefully, from additional market demand enabled by future reductions in the costs of access to space.

The annual payload weight to orbit represented by this model and the annual costs for current launch vehicles to launch the model are shown in figures 5 and 6, respectively. The U.S. Government launches 660,000 pounds of payload to space annually at a total cost of \$6.7B dollars.

Uniform costing guidelines were developed using conventional weight-based estimating algorithms to allow direct comparison of all alternatives. It was recognized that innovative and potentially lower cost strategies based on major management, contracting, and operating changes might be considered by some, but not all, of the option teams. Therefore, it was decided that these changes were to be treated as excursions to the "business-as-usual" mode.

It was also decided that the commercial traffic estimates of the mission model were to be used for fleet sizing and as a basis for estimating the production base. However, since the principal study aim was to reduce launch costs to the government, the cost projections of the options were to include only government-sponsored missions.

Vehicle	NASA Plus DOD	Commercial	All
Pegasus/Taurus	4 at 1k = 4k	8 at 1k = 8k	12k
Delta	9 at 10k = 90k	3 at 10k = 30k	120k
Atlas/Centaur	5 at 18k = 90k	3 at 18k = 54k	144k
Titan/SRMU/IUS/Centaur Shuttle/RSRM	3.3 at 4k = 156k	0	156k
• S.S. <i>Freedom</i>	5 at 36k = 180k	0	180k
• Low-Earth Orbit	3 at 47k = 141k	0	141k
Totals	661k	92k	753k

• k = weight in thousands of pounds

• Payload weight expressed in 28° low-Earth orbit equivalent, except Space Station (220 nmi at 56° inclination)

FIGURE 5.—Mission model—annual weight to orbit.

Vehicle Class	NASA	DOD	Total
Pegasus/Taurus	2 at 13M = \$26M	2 at 13 = \$26M	\$52M
Delta	3 at 50M = 150M	6 at 50 = 300M	450M
Atlas/Centaur	2 at 115M = 230M	3 at 115 = 345M	575M
Titan/IUS or Centaur	0.3 at 375M = 125M	3 at 375 = 1,125M	1,250M
Shuttle	Annual Program Costs = 3,850M	—	3,850M
Infrastructure	—	526M	526M
Total	\$4,381M	\$2,322M	\$6,703M

• All costs in FY93 dollars, millions.

FIGURE 6.—Current fleet launch costs.

## Organization

The Access to Space Study was directed by Arnold Aldrich, Associate Administrator for Space Systems Development, NASA Headquarters. The leaders of the three option teams were Bryan O'Connor, NASA Headquarters, and Jay Greene, Johnson Space Center (JSC) for Option 1; Wayne Littles and Len Wurlund, Marshall Space Flight Center (MSFC) for Option 2; and Michael Griffin, Headquarters, and Gene Austin, Marshall Space Flight Center, for Option 3.

Mr. Aldrich formed a senior-level steering group to periodically review progress and provide advice. This steering group included members from NASA Headquarters and field installations, as well as representatives from the Department of Defense, the U.S. Air Force, and the Office of Commercial Programs in the Department of Transportation.

A small group of NASA Headquarters staff, reporting to the study director, was to analyze the team reports, make strawman assessments and recommendations, and present them to the steering group and the director. The final study conclusions, presentations, and report were to be prepared by this group. The study organization is shown in figure 7.

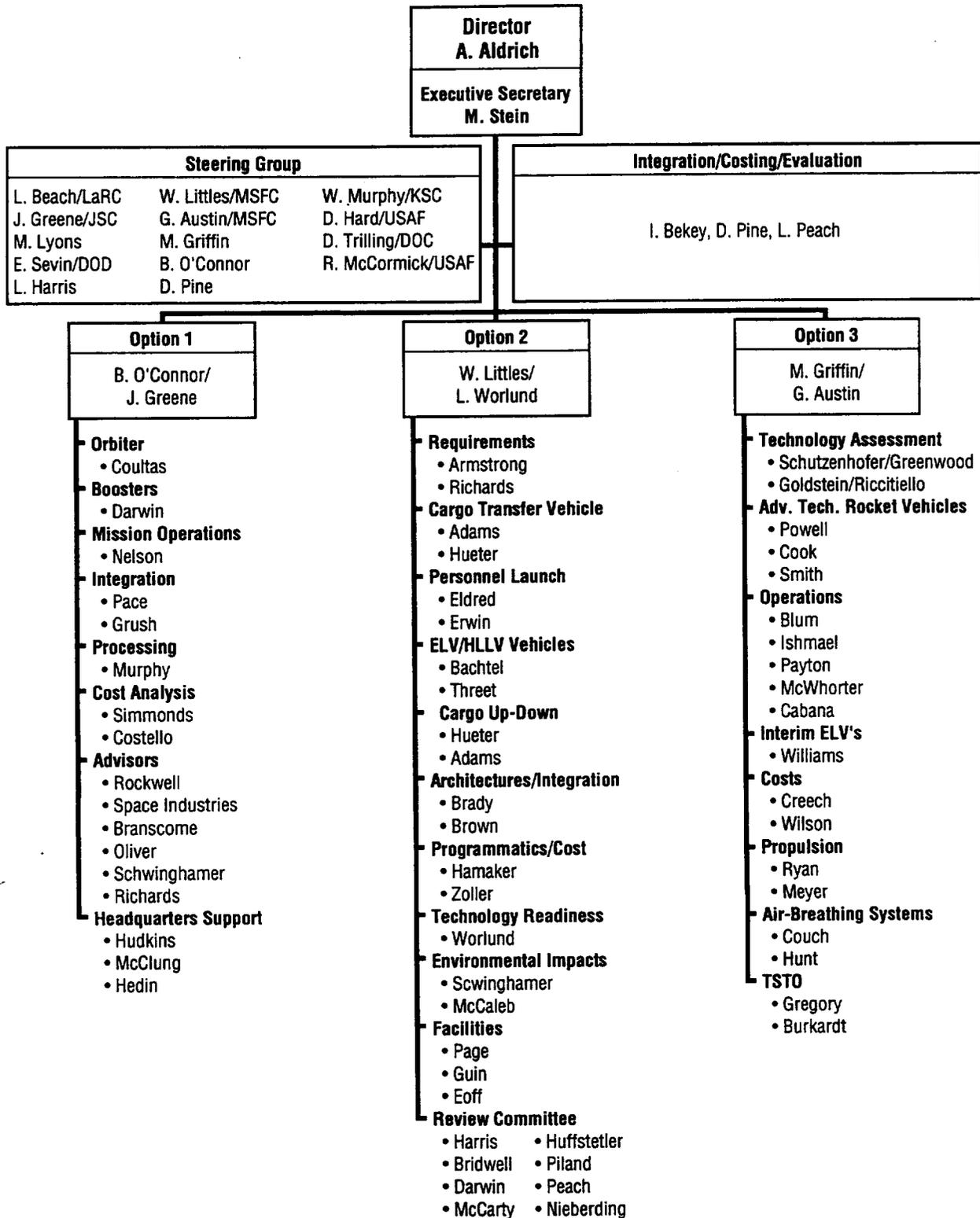


FIGURE 7.—Study organization—Access to Space.

# Description of the Option Teams' Analyses

The three option teams each characterized and analyzed a number of alternative vehicle designs and vehicle architectural mixes. They eventually settled on a small number of principal architectures to analyze in depth. These are shown in figure 8 in order to provide an overview and perspective of the options teams' detailed activities.

Option 1	Option 2	Option 3
Shuttle-Based	Conventional Technology	New Technology
<ul style="list-style-type: none"> <li>• Retrofit: Evolutionary improvements. Keep the current ELV fleet.</li> <li>• New Build: Above changes plus major internal mods; new orbiter. Keep the current ELV fleet.</li> <li>• New Mold Line: Above changes plus major external mods; new orbiters and boosters. Keep the current ELV fleet.</li> </ul>	<ul style="list-style-type: none"> <li>• 84 configurations with differing crew carriers, cargo vehicles, stage configurations, engine types, and number of new vehicles. Reduced to four primary candidate architectures:               <ul style="list-style-type: none"> <li>- (2A): New large vehicle                   <ul style="list-style-type: none"> <li>• Keep Atlas, Delta ELV's</li> <li>• HL-42 plus ATV</li> </ul> </li> <li>- (2B): New lg. and sm. vehicle                   <ul style="list-style-type: none"> <li>• Keep Delta ELV</li> <li>• CLV-P for crew plus cargo</li> </ul> </li> <li>- (2C): New lg. and sm. vehicle                   <ul style="list-style-type: none"> <li>• Keep Delta ELV</li> <li>• HL-42 plus ATV</li> <li>• Hybrids; STME engines</li> </ul> </li> <li>- (2D): New lg. and sm. vehicle                   <ul style="list-style-type: none"> <li>• Keep Delta ELV</li> <li>• HL-42 plus ATV</li> <li>• RD180/J2S engines</li> </ul> </li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>• Single-stage-to-orbit all rocket               <ul style="list-style-type: none"> <li>- With and Without ELV's</li> </ul> </li> <li>• Single-stage-to-orbit air-breather/rocket               <ul style="list-style-type: none"> <li>- No ELV's</li> </ul> </li> <li>• Two-stage-to-orbit air-breather/rocket               <ul style="list-style-type: none"> <li>- No ELV's</li> </ul> </li> </ul>

FIGURE 8.—Principal architectural alternatives examined.

The results and recommendations of each option team are presented below. The recommendations of these option teams are assessed beginning in the Option Team Down-Selects section, and study conclusions are then drawn.

## Option 1 Team Analysis

### Objectives

The premise of the overall Access to Space Study was that any design options that would replace the Space Shuttle with equal capability would have a price tag on the order of \$10B or more. The challenge for Team 1 was to see what savings could be instilled in the Space Shuttle Program through changes made to the hardware for a similar or smaller cost. The study delved into all subsystems on the Space Shuttle vehicle and stressed interaction between the Kennedy Space Center (KSC) operations representatives and the subsystem engineers to address current vehicle design features that affect operability and cost.

The Option 1 team addressed hardware changes only. Contract and management structure were not addressed, as it was felt that the mainline program is putting strong emphasis on this aspect of the program and, to be effective, recommendations in this area must come from within the program. However, the portion of the Space Shuttle budget that is directly affected by the hardware is only about 30 percent. This situation thus limited the attainable cost savings by Option 1 and emphasized the need for the program to continue making significant gains in program management.

It is recognized that the Space Shuttle Program has already implemented a management plan in FY91 aimed toward reducing operations costs. These program-imposed target reductions have a goal of reducing operations costs by 37 percent by FY96. As of FY94, the program has achieved a 29 percent operating cost reduction against an FY92 baseline.

## Study Process and Methodology

Figure 9 depicts the overall process used in the Option 1 study. The first step in the process was to identify those aspects of the design of the Space Shuttle system that significantly contribute to the cost of operations. Experts—including Space Shuttle Projects, Ground and Flight Operations, and Engineering personnel—provided inputs that were integrated into a list of approximately 90 cost drivers. From the cost drivers, the team derived requirements and developed in excess of 200 candidate changes to the current configuration vehicle that, if implemented, would satisfy the requirements. A concurrent team of engineering, design, operations, and cost personnel evaluated the candidate implementations in terms of technical feasibility and complexity, cost, and operations. The requirements-implementation-evaluation sequence was iterated as necessary to optimize selection and refine the list. All the information associated with this process was captured in an electronic data base to provide flexibility in analyzing the data. This data base was documented as part of the final report of this study.

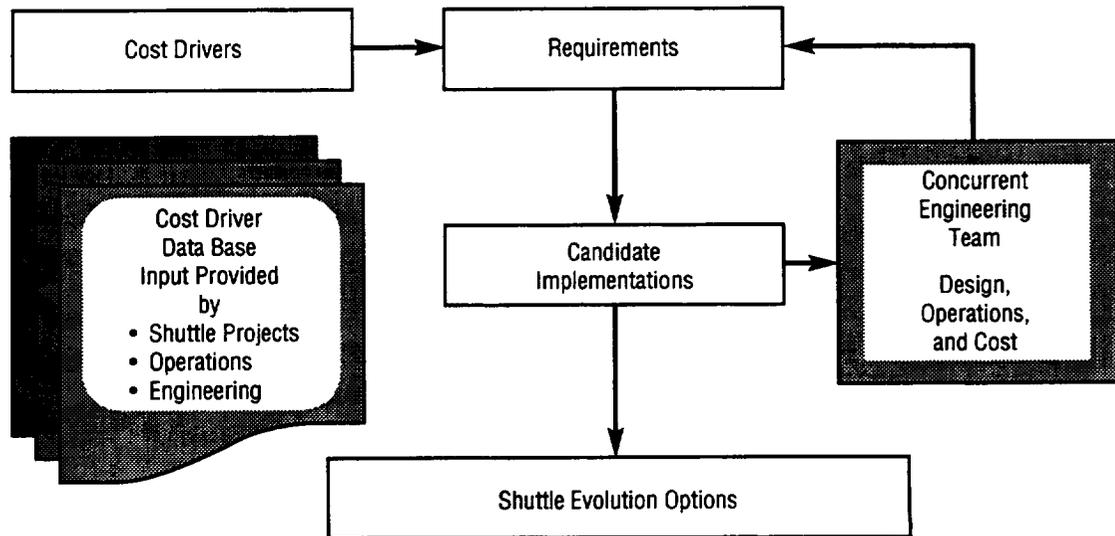


FIGURE 9.—Shuttle evolution study process.

### Shuttle Evolution Alternatives

The changes selected from the data base were integrated into three specific evolution alternatives—a Retrofit Alternative, a New Build Alternative, and a New Mold-Line Alternative. In the Retrofit Alternative, it is assumed that the improvements of the current Shuttle Vision 2000 improvement plan have been accomplished and that modifications selected can be made during an extended Space Shuttle orbiter modification period. The New Build Alternative included many of the Retrofit Alternative improvements and additional modifications that require a new orbiter to be built. For this alternative, major internal modifications can be made, but the outer mold-line of the orbiter and associated current aerodynamic characteristics would be retained. The New Mold-Line Alternative altered the aerodynamic characteristics of the orbiter to accommodate major center of gravity shifts or other engineering changes. As the studies proceeded, it became apparent that from a purely economic point of view there was no compelling reason to alter the aerodynamics of the orbiter. Efforts on the New Mold-Line Alternative were subsequently discontinued and the emphasis was placed on the Retrofit and New Build Alternatives.

## Assumptions and Guidelines

The following summarizes key assumptions and guidelines made for this study.

- The primary criterion for selecting candidate implementations is reduction in operations cost.
- For the purposes of selection, only development costs are considered. Production and retrofit costs are treated at the system level.
- Fleet sizing is assumed to remain at four.
- Flight rate is assumed to be eight Space Shuttle flights per year.
- The new start would be in 1998.

## Retrofit Alternative

A number of changes would be implemented in this alternative. They are illustrated in figure 10. A new thermal protection system (TPS) was proposed to replace one-third of all insulation tiles with a new toughened rigid ceramic tile. The areas selected were the damage-prone areas. In addition, changes were proposed to the thermal blankets, the tile bonding method, the tile gap fillers, and the hot body structure. The rudder/speedbrake and body flap were converted from a tile system to a hot body structure. The orbital maneuvering system (OMS)/reaction control system (RCS) propellant selection remained hypergolic monomethylhydrazine (MMH) and nitrogen tetroxide ( $N_2O_4$ ); however, both component reliability and accessibility were greatly improved.

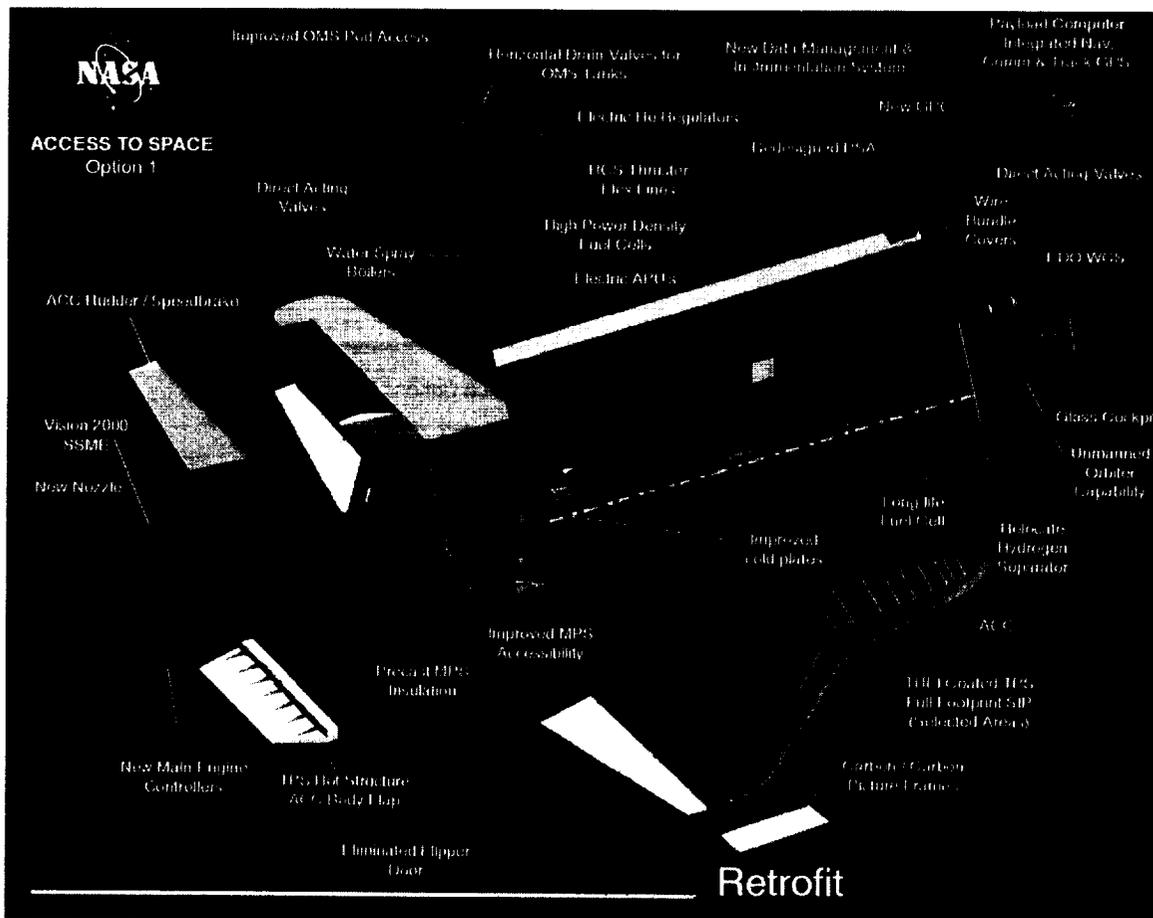


FIGURE 10.—Retrofit alternative.

The new avionics system includes a new integrated communication system, a new navigation system based on the Global Positioning System (GPS and differential GPS), and a new data management system. The new avionics system reduces the number of line replaceable units (LRU's) in the forward avionics bays, resulting in elimination of avionics bays 3a and 3b. The middeck lockers were relocated to where avionics bays 3a and 3b were, allowing improved accessibility into bays 1 and 2.

The new mechanical and electrical power system replaced the hydrazine auxiliary power system with an electrical-based auxiliary power system powered by three dedicated high-density fuel cells. In addition, changes were made to the hybrid load controller assemblies, the instrumentation power system, the fuel cells, and the electrical wire protection system. The major changes to the Environmental Control and Life Support System (ECLSS) were the addition of quick disconnects for easier access, elimination of the need for ground support equipment (GSE) cooling post-landing, and an assortment of other minor changes.

Modifications to the orbiter structure focused on replacement of the boron/aluminum struts on an attrition basis with more robust struts, the capability to inspect for corrosion on the rudder/speedbrake, and elimination of the wing flipper door replacement accomplished by modifications to the wing design.

Minor modifications were made to the orbiter's main propulsion system (MPS). The Space Shuttle main engine (SSME) was baselined to use the year-2000 configuration engine which includes advanced technology fuel and oxidizer turbopumps, a large throat main combustion chamber, a phase II powerhead and single coil heat exchanger, and block II controller improvements. In addition, a new main engine controller would be brought on-line.

The higher performance super-lightweight tank (SLWT) design would be used for the external tank (ET), along with an assortment of other modifications. The modifications to the solid rocket boosters (SRB's) included replacing the hydrazine auxiliary power unit (APU) with a solid propellant gas generator and utilizing laser-initiated pyrotechnics.

#### **New Build Alternative**

This alternative included many of the changes described for the Retrofit Alternative and, in addition, added the following changes—illustrated in figure 11—including enhancements to the thermal protection system, orbital maneuvering system/reaction control system, mechanical and electrical power system, Environmental Control and Life Support System, structural system, Space Shuttle Main Engine, and solid rocket booster.

The thermal protection system retrofitted all blankets and tiles with new improved blankets and toughened rigid ceramic tiles. The orbital maneuvering system/reaction control system was converted to an oxygen and ethanol-based propellant system. This new on-orbit propulsion system was designed to meet current volume envelopes, redundancy requirements, and on-orbit and entry impulse requirements.

The auxiliary power system was converted from a complete mechanical power system to an electro-mechanical actuator (EMA) system supplied by three dedicated high-density fuel cells. The Environmental Control and Life Support System replaced the ammonia boiler with a cryogenic boiler system. The structure was changed to incorporate a modified lower fuselage skin, additional access ports, and selected aluminum-lithium (Al-Li) replacements. The Space Shuttle main engine was converted from hydraulics to electro-mechanical actuation power. The solid rocket booster was converted from hydraulics to an electro-mechanical actuation system.



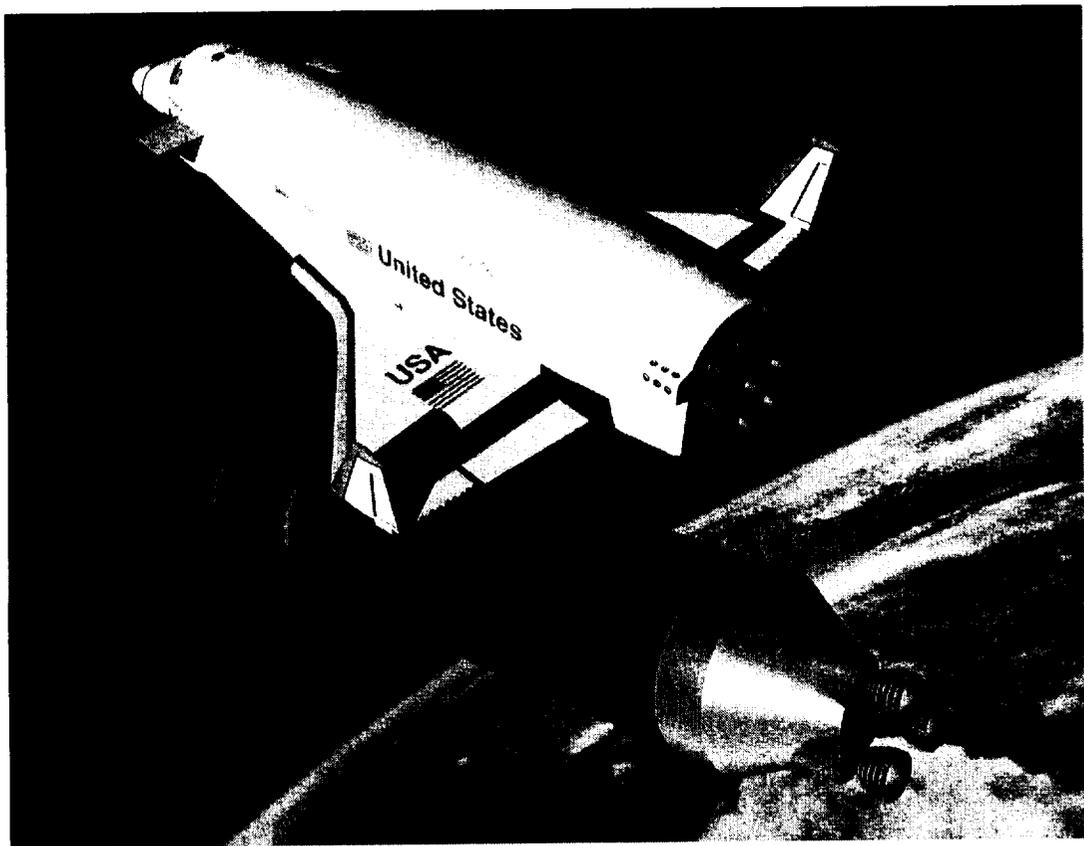


FIGURE 12.—New mold line.

	Option 1	Options 2 and 2A		Option 3	Options 4 and 4A		Option 5
Propellant	lox/LH <sub>2</sub>	lox/RP-1	lox/RP-1	Hybrid	Reusable	Expendable	Flyback lox/RP-1
Engine Type	STME	STBE	F-1A	Pressure	SSME	STME	Hi PC Engine
No. Engines/Booster	4	4	1	1	3	3	4
Thrust SL (klbf)	518.6	513	1,800	2,887	375	552	660
Booster Diameter (ft)	18	15.3	14.7	17.0	ET	ET	15
Booster Length (ft)	178.1	151	148	170.2	ET	ET	147

Some of these options may be attractive. Requires further study.

STBE—Space Transportation Booster Engine

FIGURE 13.—STS booster/propulsion options.

### Additional Means of Increasing Safety and Decreasing Cost

In addition to defining implementations for the above evolution alternatives, two additional systems were evaluated as add-ons. They were an auxiliary crew escape system and an uncrewed orbiter system. The approach for the crew escape system was to evaluate concepts that would provide a backup system for returning the crew for the full ascent phase of the mission. However, concepts that would work above 140,000 feet resulted in prohibitive weight/performance penalties. Therefore the study quickly narrowed in on concepts which would work below 140,000 feet. Three detailed concepts were defined. They were a five person ejection seat system, an eight person ejection seat system with an extended flight deck, and an eight person escape pod system. The mass penalties ranged from 1,746 pounds for the five person option to 7,588 pounds for the pod. The center of gravity was moved significantly forward in all three concepts, resulting in severe restrictions on payload placement. These alternatives are illustrated in figure 14.

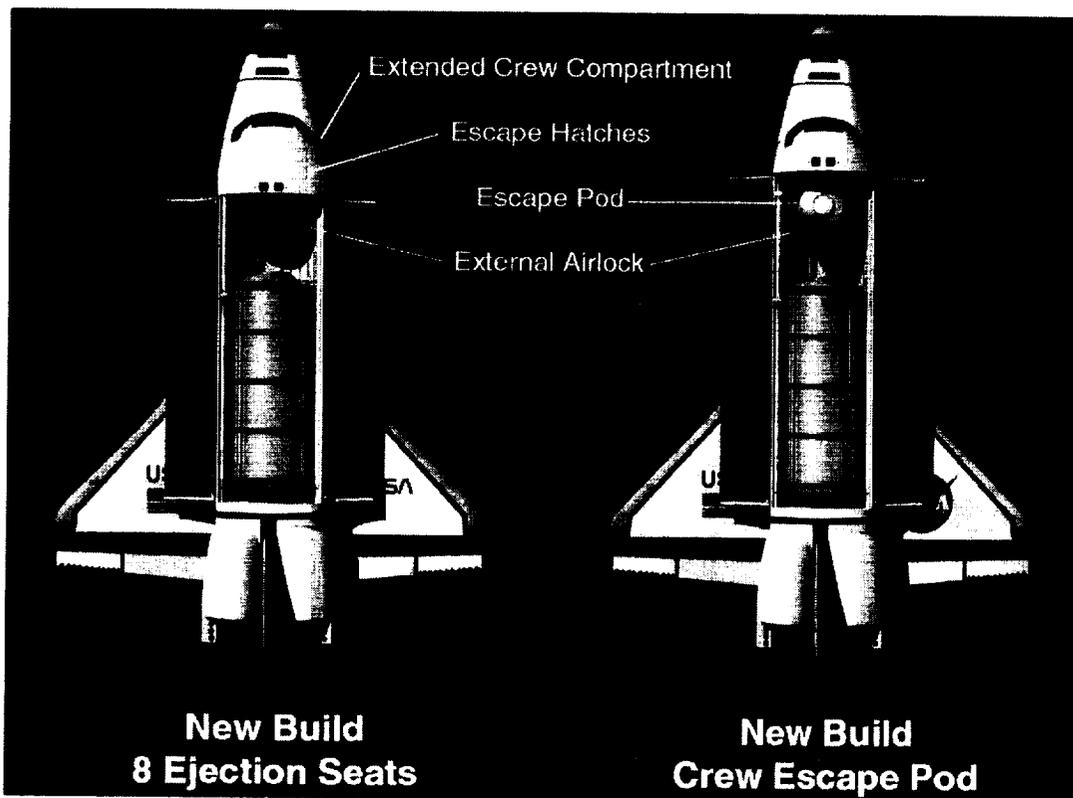


FIGURE 14.—Crew escape comparison.

An uncrewed orbiter system was also evaluated. The new avionics system proposed for all of these alternatives would have the increased capability to allow for automation of the ascent and entry functions currently performed by the pilot and commander. The main intent of this new system function was to augment current flights with uncrewed commercial and DOD satellite launches. It was viewed that these missions do not require an on-orbit crew. The Shuttle system could be utilized in this configuration (uncrewed) for general satellite launches. An associated increase in flight rate could result in a significant reduction in per-flight launch cost.

The second important advantage of an uncrewed orbiter system would be as a test platform for future Space Transportation System (STS) evolution or single-stage-to-orbit vehicle technology. New systems could be evaluated during uncrewed missions and then be baselined for use on crewed missions.

The uncrewed concept defined by the study resulted in an increase of 10,000 pounds performance and a shift of the center of gravity 26 inches back. This performance gained would have to be balanced with payload location or "ballast." The orbiter was not dedicated to either the uncrewed or crewed configuration and could be converted between either mode in the normal processing flow.

## Subsystem Improvement Descriptions

### Thermal Protection System

The flight history of the Space Shuttle has conclusively demonstrated the operational effectiveness of the existing orbiter thermal protection system. However, several design and materials improvements have been identified that have the potential to significantly reduce orbiter thermal protection system processing requirements and costs.

Tile damage from the normal flight environment, runway debris impacts, and raindrop impingement can be reduced by utilizing a thicker, tougher densification coating known as toughened unipiece fibrous insulation (TUFI). The TUFI is compatible with the current LI-2200 and FRCI-12 tiles, as well as the advanced HTP and AETB tile substrates. The TUFI, which is a highly porous coating, may simplify tile rewaterproofing operations by enabling the direct absorption of a spray-on waterproofing agent through the coating to the tile substrate, an attractive alternative to the current procedure of individually injecting tiles with DMES.

An advanced organic blanket consisting of polybenzimidazole (PBI) felt has been proposed as a replacement for felt reusable surface insulation (FRSI). The PBI has a reuse temperature limit of 900+ °F. Two advanced ceramic blankets—tailorable advanced blanket insulation (TABI) and composite flexible blanket insulation (CFBI)—have been proposed as replacements for AFRSI. The TABI is an integrally woven fabric, while CFBI consists of a multilayer assembly of foils and fabrics sewn together into a blanket. Both TABI and CFBI can be reused without replacement below temperature limits of approximately 2,000 °F.

Because tile removal is required in order to replace filler bars charred by high-temperature gap flows, the elimination of filler bars through the use of full-footprint SIP should significantly reduce thermal protection system maintenance time. In areas subject to high temperature gap flows, reusable ceramic Ames gap fillers will be employed.

Thermal protection system technology development programs, involving both high-temperature waterproofing agents and new rewaterproofing techniques, are currently under way at the NASA Ames Research Center (ARC). The ARC is pursuing the development of a "permanent" ceramic waterproofing agent with the goal of matching the reuse temperature limit of ceramic tiles, approximately 2,700 °F.

### Orbital Maneuvering System/Reaction Control System

The Retrofit Alternative retained the hypergolic based system, while the New Build Alternative converted to a liquid oxygen (lox)/ethanol-based system.

For the Retrofit Alternative, the study concluded that it would be too difficult to convert the current orbiter fleet to a new on-orbit propulsion system. Instead, the high maintenance rate of the current system and inaccessibility of numerous components would be addressed. The design changes selected were to redesign the primary thruster engine valves, helium quad check valves, helium regulation system, quick disconnects, orbiter main engine (OME) ball valve seals, and aft thruster feedline alignment bellows. The current pilot-operated valves on the primary thruster would be replaced with new direct-acting valves. The seat design would be similar to that of the vernier thrusters, which have a lower failure rate than the primary thruster valves. The expected drop in failure rate would result in lower hardware maintenance costs. Both the helium quad check valve and mechanical regulator components would be replaced with an electronic regulator system installed with dynatube fittings.

The new electronic regulator system would be designed to be propellant insensitive and capable of being fully checked out on orbit. When removal and replacement is required, the dynatube fittings would eliminate tube cuts that can result in small metal chips contaminating the internal system. These metal chips are currently a major cause of excessive leakage rates that are occurring on many orbital maneuvering system/reaction control system helium components. The quick disconnects would be redesigned to be propellant insensitive. The orbiter main engine ball valve seal would be replaced with one that does not leak. The aft thruster feedline alignment bellows would be replaced with flexlines based on the forward thruster design. In addition to the above redesigns, additional access doors would be added to the pods.

The oxygen/ethanol propellant combination was selected because it eliminates the hypergolic servicing infrastructure, reduces the number of KSC-unique fluids by one, fits within the current mold line, eliminates SCAPE suit operations, reduces or eliminates serial processing required by the current orbital maneuvering system/reaction control system, and eliminates a number of causes of orbital maneuvering system pod removal. In addition to the above, the concept selected provides both the same redundancy level and total impulse level that the current orbital maneuvering system/reaction control system provides. It is expected that the operational cost for an oxygen/ethanol based on-orbit propulsion system will be significantly lower than the current hypergolic-based system.

### **Avionics**

Major changes were made to the communications and tracking system; the guidance, navigation, and control system; and the data management and instrumentation system, thereby reducing the number of line replaceable units. These changes led to the elimination of avionics bays 3a and 3b. This enables the middeck lockers to be relocated to this location, resulting in improved accessibility to avionics bays 1 and 2.

The current Communications and Tracking system was replaced with a more integrated system. The new system resulted in fewer line replaceable units by combining the function of the Communications Security (COMSEC) unit, the network signal processor (NSP), and the transponder into a single line replaceable unit. A new payload computer would combine the functions of the payload signal processor (PSP) and payload interrogator. The power amp and preamp line replaceable unit to the antenna switch would be eliminated. The pulse-code modulation master unit (PCMMU) and payload data interleaver (PDI) functions would be incorporated into the new general purpose computers (NGPC) and payload computer. Increased data transmission rates would eliminate data downlist restrictions, resulting in a single data format and deletion of the FM processor. A self-test capability would be incorporated to provide fault isolation down to the line replaceable unit while installed on the vehicle and down to subassembly during bench-level testing.

The current navigation system would be completely changed to a new inertial navigation system utilizing embedded GPS, embedded radar altimeter functions, differential GPS capability, and IFOG gyros. A GPS antenna grid of six would be added to replace the star trackers. In addition to the star trackers, the inertial measurement unit (IMU)/high accuracy inertial navigation system, tactical air navigation (TACAN), microwave scanning beam landing system (MSBLS), accelerometer assemblies, and rate gyro assemblies would be eliminated.

The data management and instrumentation system would be upgraded to state-of-the-art computers. The improved general purpose computers would incorporate fiber optic cables for coupling to the multiplexer/demultiplexers (MDM's). Both the output/input recorders and mass memory unit (MMU) would be changed to optical storage with the MMU installed in the general purpose computer. The multifunction electronic display subsystem (MEDS) that is currently under design would also be incorporated. The MDM's would be redesigned to allow for individual cards to be replaced while still installed on the vehicle. The overall

avionics heat load would be reduced and would allow avionics to be totally cooled by air purge only during all ground turnaround operations. A dedicated ground-located general purpose computer (e.g., ground brain) would be capable of connecting directly into the MDM's and either receive instrumentation data or command other subsystems without the flight general purpose computers on-line. Finally, the backup flight software would be eliminated.

### **Orbiter Mechanical and Electrical Power Systems**

Evolutionary improvements for the orbiter mechanical and electrical subsystems were selected because of their ability to reduce operations cost and improve system safety in the following areas.

- Hazardous ground operations associated with servicing the auxiliary power unit (APU) hydrazine propellant and the high-pressure hydraulic systems.
- Ground operations associated with handling and disposing of toxic hydrazine propellants and hydraulic fluids.
- Flight safety issues associated with the hydrazine auxiliary power units and hydraulics.
- Excessive cycling of the orbiter systems to support ground checkout.
- Repair and replacement of fuel cells due to their limited life.
- Repair and replacement of electrical power distribution and control (EPDC) line replaceable units.
- Repairing accidental damage to electrical wires which occur during ground operations.

An electric auxiliary power unit (EAPU), using high power density fuel cells (HPDFC) for power, was determined to be the most cost-effective replacement for the hydrazine auxiliary power units for the Retrofit Alternative. A modified water spray boiler (WSB) was used for cooling the HPDFC's. For a new-build orbiter, electro-mechanical actuators were selected to replace the auxiliary power units and hydraulic system using high power density fuel cells to supply electro-mechanical actuator electrical power.

The existing fuel cells would be replaced with the long life fuel cell with single-cell instrumentation. The new fuel cells would have a lifetime five times longer than the current fuel cells. The improved instrumentation and increased life would result in reduced line replaceable unit removal and replacement (R&R) costs and associated logistics costs.

Redesigned hybrid device controllers (HDC's) would be resettable and would reduce the number of HDC removal and replacement occurrences. A redesigned load controller assembly (LCA) would also be incorporated which would permit for HDC replacement without load controller assembly removal from the orbiter.

The ability to provide power to selective components on the orbiter would be implemented in both design alternatives to varying degrees. Both alternatives would incorporate a dedicated instrumentation power bus and conditioning equipment for selected instrumentation, multiplexer/demultiplexers, and signal conditioners. The electro-mechanical actuators for the new-build orbiter would be powered and controlled through ground support equipment to facilitate ground processing. These improvements would significantly reduce the amount of operating time on orbiter components, thereby increasing the mean time between repair.

Finally, protective covers would be provided for orbiter wire bundles that are located in frequently accessed areas and bundles would be rerouted for easier access. This modification would reduce wire damage that occurs during ground operations.

## **Environmental Control and Life Support System**

Quick disconnects would be installed on high-maintenance components within the Freon™ and water (H<sub>2</sub>O) coolant loops, allowing for removal and replacement without requiring a complete deservice of the coolant system. In addition, built-in test (BIT) equipment would be added for the radiator, ammonia, and flash evaporator system controllers, eliminating the need for drag on ground support equipment in the Orbiter Processing Facility (OPF). Midbody and aft cold plate thickness would be increased to reduce damage done to cold plates during line replaceable unit removal and replacement.

The current waste compartment system (WCS) must be removed from the orbiter and shipped to the Johnson Space Center for cleaning and refurbishment after each flight. The WCS developed for the extended duration orbiter (EDO) would replace the existing WCS on all vehicles. The new WCS uses a compactor/canister stowage concept, and does not need to be removed from the orbiter for cleaning and refurbishment.

Relocating the H<sub>2</sub> separator into the midbody area would eliminate vacuum vent inerting ground support equipment and reduce launch countdown manual operations. Safety would also be improved since there would be no H<sub>2</sub> stored within the 2-inch overboard dump line during launch countdown.

The current PSA is designed as two separate pieces, and access to remove these units is difficult. For all vehicles, the PSA would be redesigned for removal as a single unit, which would allow easier removal and reinstallation on the ground.

The new avionics being installed in all vehicles only require cold plate cooling. Therefore, avionics bay 1, 2, and 3 heat exchangers (HX's), six associated fans, and the inertial measurement unit (IMU) heat exchanger and fan can be eliminated.

The ammonia boiler system would be replaced with a cryogenic boiler system on new-build vehicles. This system would provide cooling at low altitudes, through landing and rollout. This system reduces the number of fluids required by the orbiter and eliminates hazardous operations associated with ammonia.

It has been determined that purge air directed through the payload bay provides sufficient cooling after landing. Therefore, the requirement for the 570-0508 cart at the runway can be eliminated. Elimination of this requirement results in fewer operations at landing and a reduction in maintenance of ground support equipment.

Currently, the extended memory unit (EMU) Personal Life Support System (PLSS) water purity requirements are higher than what can be provided by the orbiter. The EMU PLSS design will be changed to allow it to use the orbiter's water supply in its sublimator. This will eliminate 2 weeks of water polishing time at Kennedy Space Center after each extravehicular activity (EVA).

## **Structural System**

For new-build vehicles, aluminum-lithium (Al-Li) would be substituted for aluminum where practical. This will result in a 3,900 pound weight savings over the current orbiter structural mass, which would offset weight increases resulting from design enhancements in other areas, as well as increase payload capability.

The current boron-aluminum (B-Al) midbody struts would be replaced with a more robust material to reduce their susceptibility to damage by technicians working around them. Currently, the midbody struts are being replaced with aluminum struts on an attrition basis. For retrofit vehicles, this would continue until all struts are replaced, resulting in a net weight increase of 200 pounds per orbiter. For a new-build vehicle, Al-Li will be substituted for the B-Al alloy, resulting in a net weight increase of about 180 pounds per orbiter.

The rudder speed brake (RSB) inner panels of the current orbiter fleet are susceptible to corrosion and, therefore, require frequent inspection. Removal and subsequent reinstallation of these panels to make repairs is difficult and time consuming. A design change to eliminate this problem would be implemented on all vehicles, reducing inspection requirements, material costs, analysis time, and precluding the need for reapplication of sealant.

The flipper door system is particularly difficult to service because of its complex design. Both the retrofit and new build vehicles would replace the flipper door system with a wing extension incorporating a piano hinge for wing access requirements. Incorporation of this new design would reduce the maintenance time required to service the wing/elevon cavity, as well as reduce weight.

For a new-build vehicle, the size of the current access ports to the aft compartment would be increased to approximately four times their current size. This would enhance installation and removal of ground support equipment, and allow more technician access at a given time. Also, with less assembly of ground support equipment inside the aft compartment required, accidental damage to components can be reduced. Access ports for other frequently serviced areas will be built into new vehicles, as well, to reduce maintenance and inspection time.

For the retrofit vehicle, access ports will be added to the orbital maneuvering system pods, providing easier access to the most frequently serviced internal components. This will allow the orbital maneuvering system pods to remain on the vehicle for certain inspections and maintenance.

Currently, hot spots seen on the orbiter mid-fuselage lower skin during reentry are handled through the use of RTV heat sinks. For new-build vehicles, the design of the mid-fuselage lower skin can be improved so that RTV heat sinks will not be required, resulting in a weight reduction of 220 pounds.

One concept for crew escape is to provide ejection seats located on the flight deck. In order to provide for this, the crew module would have to be extended 4.5 feet into the payload bay.

### **Main Propulsion System**

Over 36 improvements to the main propulsion system were suggested by the members of the Option 1 team. Half of the implementations were selected by the both the Retrofit and New Build Alternatives. The hardware improvements fell into two categories: improved system operability and items that could be classified as preplanned program improvements.

Modifications to the main propulsion system include component changes, deletions, and additions. Only the outboard LH<sub>2</sub> and LO<sub>2</sub> manifold fill and drain valve assemblies were deleted. New components include leak check/purge ports between the GHe interconnect and the check valves, instrumentation for LH<sub>2</sub>/LO<sub>2</sub> fill/drain and LH<sub>2</sub> recirculation system, purge ports to facilitate orbiter GH<sub>2</sub>/GO<sub>2</sub> system welding operations, protective covers for flex hoses, filters for the inlets/outlet of the LH<sub>2</sub> and LO<sub>2</sub> manifold relief pre-valves (6) and inboard fill/drain relief valves, and fill/drain and pre-valve inspection ports. Several components would be redesigned including the helium check valves, LH<sub>2</sub>/LO<sub>2</sub> relief valves, and the K-seals on rough finished fittings. The foamed-in-place insulation on the engine interface would be changed to precast insulation.

Operational changes would also be approved for the main propulsion system. These changes include provisions for orbiter flange lapping tools and certification of the SPC and/or NSLD to perform required lapping in the field instead of having to return to the vendor, a centralized new vacuum jacket readout panel and vacuum jacketed line repair techniques, extended certification on the external tank/orbiter umbilical joint line assemblies, particle induced noise detection (PIND) testing on valve position switches, and extended certification on limited life temperature probes.

### **Space Shuttle Main Engine**

The only implementations selected for the Retrofit Alternative were the Vision 2000 Space Shuttle main engine and a new main engine controller. The Vision 2000 Space Shuttle main engine implementation, which has already been approved by the Space Shuttle Program, consists of new Alternate Turbopump Development fuel and oxidizer pumps, a large throat main combustion chamber (MCC), a phase II+ powerhead with a single cooling coil, and block II controller improvements. The Vision 2000 Space Shuttle main engine improvements enable more complete servicing of the engines on the vehicle and allow the engines to remain on the vehicle for up to 10 flights. The new main engine controller implementation goes beyond the changes made in the block II controller. The new main engine controller incorporates the orbiter engine interface unit (EIU) function internally and allows the EIU to be eliminated. The new controllers also provide increased capability for launching with failed transducers by providing a more complex algorithm to determine which transducer is providing a faulty reading and eliminating it from the voting scheme.

The New Build Alternative selected the retrofit implementations along with electro-mechanical actuators for the Space Shuttle main engine thrust vector control (TVC) system and propellant valves. The Space Shuttle main engine's electro-mechanical actuators will work in conjunction with the electro-mechanical actuators used for aerosurface control and landing gear operations on the new-build vehicle. Complete elimination of the hydraulic system on the orbiter is now possible. The Space Shuttle main engine's electro-mechanical actuators would be powered by high-density fuel cells in the same manner as the other electro-mechanical actuators on the vehicle.

### **External Tank**

Implementations for the external tank addressed increased performance and reductions in manufacturing complexity. The first implementation selected was the super-lightweight tank, which adds 8,000 to 12,000 pounds of Shuttle payload performance due to the lower weight of the external tank. An assumption was made that the development of the super-lightweight tank would be implemented by the baseline program.

The manufacturing-related implementations selected include alternative thermal protection system concepts and an electro-magnetic acoustic transducer (EMAT). The thermal protection system alternatives address the use of composites and heat sinks instead of sprayed-on foam. This reduces the labor involved with the thermal protection system application. The EMAT is a new nondestructive technique for weld inspection. This new technique eliminates today's labor intensive dye penetrant inspection. There are opportunities to use the technique in other areas of orbiter processing as well.

### **Solid Rocket Booster**

Solid rocket booster implementations focused on reducing the labor intensive operations associated with processing the boosters. Alternative boosters were considered for replacement of the solid rocket boosters. Boosters considered were the advanced solid rocket motor (ASRM), liquid rocket boosters (LRB's) (LO<sub>2</sub>/RP-1), hybrids, and flyback LRB's. The flyback LRB was the only booster configuration that had a life cycle cost comparable with the solid rocket boosters. Discussion of the flyback booster provided is given in the Approach, Ground Rules, and Organization section.

Improvements recommended for the solid rocket boosters included a solid propellant gas generator (SPGG) replacement for the hydrazine auxiliary power units, electro-mechanical actuator replacement of the thrust vector control system along with an alternate power source to replace the hydrazine auxiliary power units, and laser-initiated pyrotechnics. The solid propellant gas generator and electro-mechanical actuator implementations are targeted to eliminate the hydrazine auxiliary power units. Past studies have shown that an electro-mechanical actuator thrust vector control system would net higher annual recurring savings than the SPGG, so this would be the preferred choice. The electro-mechanical actuator thrust

vector control eliminates the hydraulics on the solid rocket boosters, as well. The laser-initiated pyrotechnics eliminate electromagnetic interference (EMI) concerns and enable complete firing circuit verification after firing line connection. The ordnance connections can be performed in the Vehicle Assembly Building (VAB) instead of late in the flow and do not require facility clears.

## Ground and Flight Operations

### Mass Properties and Performance

The mass properties and performance for the Retrofit and New Build Alternatives were calculated by determining the incremental effects of each implementation chosen. A detailed mass breakdown of Orbiter Vehicle (OV) 105 was used as a point of comparison for the analysis.

Many of the hardware implementations selected require significant changes in the subsystem definitions. Some changes overlap several subsystems. In some instances components are removed, while other combinations add hardware. Most implementations modify the existing components. The avionics implementations reduced the number of components significantly, which reduced the system mass by over 900 pounds. However, other subsystem implementations selected by the Retrofit Alternative offset the mass saving of the avionics system.

The net effect for the Retrofit Alternative was to increase the vehicle mass by 58 pounds. The center of gravity (CG) for the Retrofit Alternative was changed more significantly by the implementations. The landed center of gravity is 5.2 inches aft of the landed center of gravity for OV-105.

The New Build Alternative was permitted to change systems more extensively, including structure. The New Build Alternative landed mass is 2,300 pounds lower than OV-105, but the landed center of gravity remained unchanged.

The performance of the Retrofit Alternative is the same as for OV-105. Approximately 55,000 pounds can be transported to a 100 nautical mile, 28.5 degree orbit. When a super-lightweight tank is used, the lift capability is increased to approximately 63,000 pounds. Performance to a 100 nautical mile orbit at an inclination of 51.6 degrees is approximately 49,000 pounds for the Retrofit Alternative.

The New Build Alternative performance is 2,300 pounds greater than OV-105 or the Retrofit Alternative. The performance to an altitude of 100 nautical miles and an inclination of 28.5 degrees is approximately 57,000 pounds. The performance with a super-lightweight tank is close to 65,000 pounds. The higher performance of the orbital maneuvering system on the new-build vehicle offers more payload capability at higher altitudes than the OV-105 or Retrofit Alternative.

### Technology Plan

The Space Shuttle evolution technology and advanced development plan for Option 1 addresses all flight-related subsystems and elements. The key technology and advanced development programs for Space Shuttle evolution are outlined below.

The development of high-temperature thermal protection system elements and/or nonhazardous thermal protection system waterproofing agents is critical to reducing thermal protection system processing costs. Further characterization of TUF1 coatings and AETB and ACC tiles is required before implementation can be achieved. Advanced flexible blankets, which will reduce operational costs through increased temperature margins, will need further advanced development work as well.

The development of propellant residue-insensitive valves will significantly reduce orbital maneuvering system/reaction control system unscheduled maintenance operations and costs. Accessing and developing low-toxicity propellants and propulsion systems, both cryogenic and storable, will eliminate many of the hazardous propellant operations at the Kennedy Space Center.

Advanced development and technology initiatives for avionics include the development of flight certified integrated guidance, navigation, and control (GN&C) units using interferometer fiber optic gyro technologies, differential GPS for terminal approach, attitude determination using GPS for inertial navigation system (INS) alignment, digital signal processing component development for communications and space flight-qualified high-definition television components that are lightweight, small volume, and low power.

The data management system must develop stable software and hardware interfaces for integration of commercially available off-the-shelf hardware that will mitigate long-term obsolescence. Improved methods of software development and maintenance must be developed using autocode generation, as well as improved software validation and verification methods.

Development of high-power density fuel cells and high voltage and high current switching technology is required for both the electrical auxiliary power unit and electro-mechanical actuator options. Advanced development of space qualified electro-mechanical actuators and electrical hydrostatic actuators should be pursued.

A technology initiative that produces a Freon-21 replacement that is nonhazardous and environmentally safe is very desirable. The development of cryogenic cooler/boiler and thermal wax pack heat rejection devices, which do not use toxic fluids such as ammonia, should be addressed.

A vehicle health management plan must be developed that focuses Agency technology funding toward specific customer needs. Particular hardware development efforts should address built-in test capabilities for mechanical systems and line replaceable unit fault isolation, robust engine health instrumentation and algorithms, on-board leak isolation, smart transducers and sensors, on-board solenoid valve current signature instrumentation, and highly reliable valve position indicators.

Structural characterization of aluminum-lithium and high-temperature aluminums should be pursued.

Development of laser implementation of the NASA standard initiator, pyrotechnic initiator controller, and safe and arm systems will reduce ground operations costs, improve system safety, and reduce the number of anomalies associated with the current pyrotechnic systems.

Many of these technology developments are applicable to new launch vehicle systems as well.

## Costing

All cost data is reported in fiscal year (FY)1994 dollars. Production costs for the solid rocket booster, solid rocket motor, external tank, and Space Shuttle main engine are recurring costs that are reflected in the baseline Space Shuttle Program budget. Wrap factors are in accordance with NASA Comptroller instructions. The program support wrap was reduced to five percent for design, development, test, and evaluation (DDT&E) and 0 percent for production. The NASA Cost Model (NASCOM) was used to estimate DDT&E and production costs and the operations savings were estimated by grass-roots methods.

Recognizing the uncertainties of the study, the following conclusions were reached.

The cost savings identified to date in the Retrofit Alternative are \$145M per year. The cost to retrofit the fleet is estimated at \$5.7B. Many of the individual changes identified in the Retrofit Alternative should be implemented in any event; however, sufficient data does not exist to recommend implementing the total package of proposed retrofit changes.

The cost savings identified to date in the New Build Alternative are \$169M per year. The fleet replacement cost is \$15B. The New Build Alternative is not cost-effective, and there are no substantial reasons to build a new fleet. Features contained in the New Build Alternative should be considered if and when a new orbiter is built.

Only the direct hardware-driven costs, about 32 percent of the Space Shuttle Program budget, were addressed by the study. Current operations cost accounting methods were found to be inadequate for accurately determining the savings from subsystem improvements. The NASCOM was not designed for estimating modifications to existing systems, and there are only limited tools available for estimating space flight operations costs.

Several recommendations were developed to improve the cost estimating capability. High quality grass-roots estimates should be developed for high pay-back items. An activity-based cost accounting system should be established to track all operations costs. New cost-estimating relationships (CER's) should be developed to improve the estimating capability in selected areas. An effort should be initiated to develop an operations cost model and a new NASCOM with factors for technical change, process improvements, and design inheritance.

## Findings

The Option 1 team found that the Retrofit Alternative was the best of the three alternatives examined. It has the lowest investment cost and about the same savings in operations costs as the others.

Providing additional crew escape capability was not recommended due to cost, weight, and center of gravity impacts, and technical risks. Several means to reduce costs further and increase flight safety were identified. One is an uncrewed orbiter, which would allow the flight rate to increase without impacting human safety, permit more flexible flight and payload assignment, increase the payload capability of the Shuttle system for uncrewed cargo delivery. Another is to replace the solid rocket boosters with flyback liquid boosters, which could increase safety and simultaneously improve operations efficiency.

The uncrewed orbiter has already had considerable definition, but the flyback booster requires further study to define cost effectiveness.

The Shuttle system is safe and highly reliable, and could support the projected national mission model through 2030. However, if the nation is to place primary reliance on the Space Shuttle for this period, the current four orbiter fleet is not sufficient. Detailed plans must be made for either orbiter replacement upon attrition or immediate expansion of the fleet size.

Many technologies have been identified that could prove useful to other concepts for future space transportation. Associated technology development should be initiated soon. Examination of new ways of doing business to address non-hardware potential efficiencies should proceed and be carried out by the Space Shuttle Program Office. Improvements to accounting methods and cost data bases should also be undertaken.

# Option 2 Team Analysis

## Objectives and Approach

The conventional technology options are requirements-driven architectures (with 1997 technology) that can replace the current launch systems in approximately 2005. These new architectures are to meet the nation's total space transportation needs—civil, national defense, and commercial—and to provide improved crew safety, acceptable life-cycle costs (affordable design, development, test, and evaluation; improved operability and annual cost reduction; and acceptable program risks), and a mission reliability of 0.98, and be environmentally acceptable. The architectures should improve commercial competitiveness, contribute to the industrial economy, enable incremental development/improvements, and provide improved capability relative to current systems.

The Option 2 approach was a multiphased process consisting of the spacecraft portion and the launch vehicle portion. Mission options that dealt with crew and cargo logistics were down-selected to three main architectural categories: (1) separate crew and cargo airframe, (2) common crew and cargo airframe with HL-42 vehicle, and (3) common crew and cargo airframe with CLV-P vehicle. Each mission option placed different requirements on the launch vehicle families.

The launch vehicle down-select process began with 84 vehicle families that were narrowed to 28, based on performance and propellant selection criteria. The 28 families were assessed in a one-on-one comparison for each mission category based on cost, safety, environment, risk, operability, and reliability. Four architectures were selected for detailed costing and were defined and analyzed. They are illustrated in figure 15.

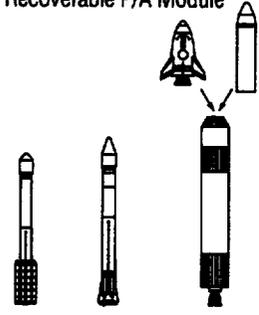
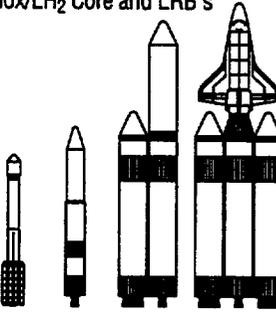
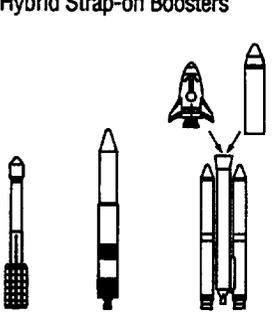
<p><b>Architecture 2A'</b></p> <ul style="list-style-type: none"> <li>• 1.5 Stage LV Family Utilizing Recoverable P/A Module</li> </ul>  <p>Delta Atlas STS/Titan Replacement</p>	<p><b>Architecture 2B</b></p> <ul style="list-style-type: none"> <li>• Parallel Burn LV Family Utilizing Iox/LH<sub>2</sub> Core and LRB's</li> </ul>  <p>Delta 20k STS/Titan Replacement</p>	<p><b>Architecture 2C</b></p> <ul style="list-style-type: none"> <li>• Parallel Burn LV Family Utilizing Hybrid Strap-on Boosters</li> </ul>  <p>Delta 20k STS/Titan Replacement</p>	<p><b>Architecture 2D</b></p> <ul style="list-style-type: none"> <li>• Series Burn LV Family Based on Low Cost/Low Risk RD-180 Russian Engine</li> </ul>  <p>Delta 20k STS/Titan Replacement</p>
<p><b>Features:</b></p> <ul style="list-style-type: none"> <li>• Delta for 10k Class</li> <li>• Atlas for 20k Class</li> <li>• STS/Titan Replacement Class                             <ul style="list-style-type: none"> <li>– HL-42 for Crew Transport</li> <li>– ATV for Cargo Transport</li> <li>– Single Engine Centaur</li> <li>– 1.5 Stage Parallel Burn</li> <li>– All Iox/LH<sub>2</sub></li> <li>– Partial Reusable (P/A)</li> <li>– SSME</li> </ul> </li> </ul>	<p><b>Features:</b></p> <ul style="list-style-type: none"> <li>• Delta for 10k Class</li> <li>• New 20k to Replace Atlas</li> <li>• STS/Titan Replacement Class                             <ul style="list-style-type: none"> <li>– Full Station Logistics Return</li> <li>– CLV-P for Crew and Cargo</li> <li>– Single Engine Centaur</li> <li>– 2 Stage Parallel Burn</li> <li>– All Iox/LH<sub>2</sub></li> <li>– Expendable LV Elements</li> <li>– Low Cost, STME</li> <li>– Commonality: Boosters/Core/20k</li> </ul> </li> </ul>	<p><b>Features:</b></p> <ul style="list-style-type: none"> <li>• Delta for 10k Class</li> <li>• New 20k to Replace Atlas</li> <li>• STS/Titan Replacement Class                             <ul style="list-style-type: none"> <li>– HL-42 for Crew Transport</li> <li>– ATV for Cargo Transport</li> <li>– Single Engine Centaur</li> <li>– 2 Stage Parallel Burn</li> <li>– Hybrid Booster/Iox/LH<sub>2</sub> Core</li> <li>– Expendable LV Elements</li> <li>– Low Cost, STME</li> <li>– Commonality: Core w/20k</li> </ul> </li> </ul>	<p><b>Features:</b></p> <ul style="list-style-type: none"> <li>• Delta for 10k Class</li> <li>• New 20k to Replace Atlas</li> <li>• STS/Titan Replacement Class                             <ul style="list-style-type: none"> <li>– HL-42 for Crew Transport</li> <li>– ATV for Cargo Transport</li> <li>– Single Engine Centaur</li> <li>– 2 Stage Series Burn</li> <li>– Iox/RP (1), Iox/LH<sub>2</sub> (2)</li> <li>– Expendable LV Elements</li> <li>– RD180/J2S</li> </ul> </li> </ul>

FIGURE 15.—Option 2 architecture overview.

## Architecture Overview

The nation's access to space is provided in 10k, 20k, and 65k pounds to low-Earth orbit (LEO), and 15k pounds to geosynchronous transfer orbit (GTO) classes. All architectures feature the Delta launch vehicle for the 10k-pound class payloads. The 20k-pound class is provided by using the Atlas launch vehicle for Architecture 2A'. Architectures 2B, 2C, and 2D use a new booster with commonality to the STS/Titan IV (TIV) replacement and a single-engine Centaur upper stage. The Space Shuttle/TIV replacement architectures are as follows: 2A'—1.5 stage with recoverable propulsion/avionics modules and reusable Space Shuttle main engines; 2B—a hydrogen-fueled parallel burn two-element vehicle that uses a liquid booster for the TIV-type missions and two liquid boosters for the STS-type missions; 2C—a parallel burn two-element vehicle using a hydrogen fueled core and hybrid boosters; 2D—a two-stage series burn vehicle with a rocket propellant (RP) fueled booster and a hydrogen fueled second stage. Architectures 2A', 2C, and 2D use a small lifting body reusable personnel launch system (HL-42) for crew transport and a cargo transfer vehicle for cargo transport. Architecture 2B uses a reusable CLV-P (approximately 70-percent scale of the STS orbiter) for transport of crew and payloads.

## Major Features of Architectures

### 20k Class Vehicle Comparisons

The 20k vehicle alternatives are compared in figure 16. For Architecture 2A', the Atlas (with evolutionary upgrades) remains throughout the mission model period. At a cost of \$85M per flight, the Atlas represents an acceptable approach if the reliability (0.89) and operational features are improved. Architectures 2B and 2C use a 20k vehicle replacement based on a hydrogen/oxygen booster with a modified Centaur upper stage (incorporates single RL-10C and structurally stable tankage with a calculated reliability of 0.99). The booster is 18 feet in diameter and uses a new low-cost space transportation main engine. The Architecture 2D 20k vehicle replacement is based on an RP-1/oxygen booster with a modified Centaur upper stage with a calculated reliability of 0.98.

### Titan IV-Class Vehicle Comparisons

Titan IV-class alternatives are compared in figure 17. For Architecture 2A', the vehicle replacement is a high reliability (0.98) 1.5 stage hydrogen/oxygen vehicle based on a 27.5 foot external tank diameter. The propulsion system is comprised of a cluster of six Space Shuttle main engines configured in 3 two-engine propulsion/avionics (P/A) modules. The two booster modules are jettisoned during ascent and recovered, while the third performs the sustainer role and is recovered after main engine cutoff. For Architecture 2B, the vehicle is an L-configuration core with single booster. The all hydrogen/oxygen vehicle utilizes a stretched 20k core (18-foot diameter) with a single 700k pound thrust engine on the core and two on the booster, and has a calculated reliability of 0.98. For Architecture 2C the vehicle is a highly reliable (0.99) parallel-burn core with hybrid boosters. The hydrogen/oxygen core is a stretched 20k core with a single 700k-pound space transportation main engine, and the boosters produce 1.5M pounds of thrust with a pump-fed oxygen supply and hydroxyl terminated polybutylene (HTPB) propellant. Architecture 2D uses a two-stage series burn vehicle with a calculated reliability of 0.98. The RP-1/oxygen first stage is 27.5 feet in diameter and utilizes RD180 engines. The second stage is a Saturn IV-B class stage, 20 feet in diameter, and uses a single J2-S engine.

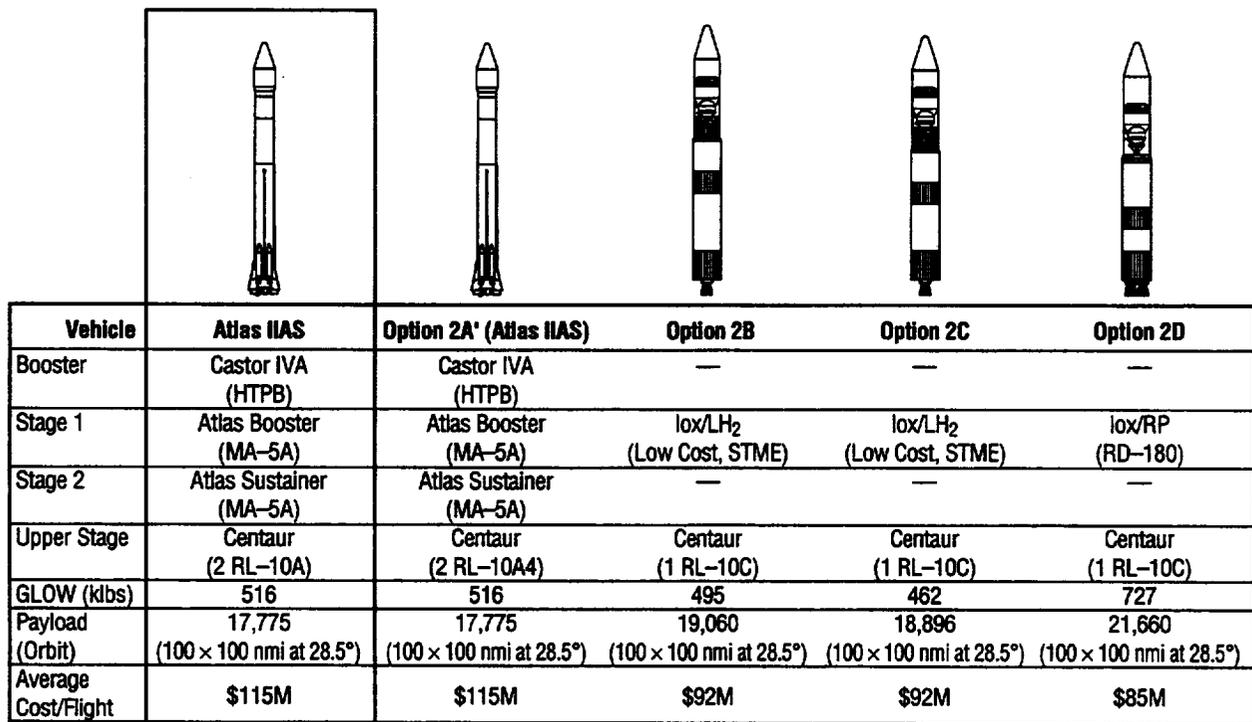
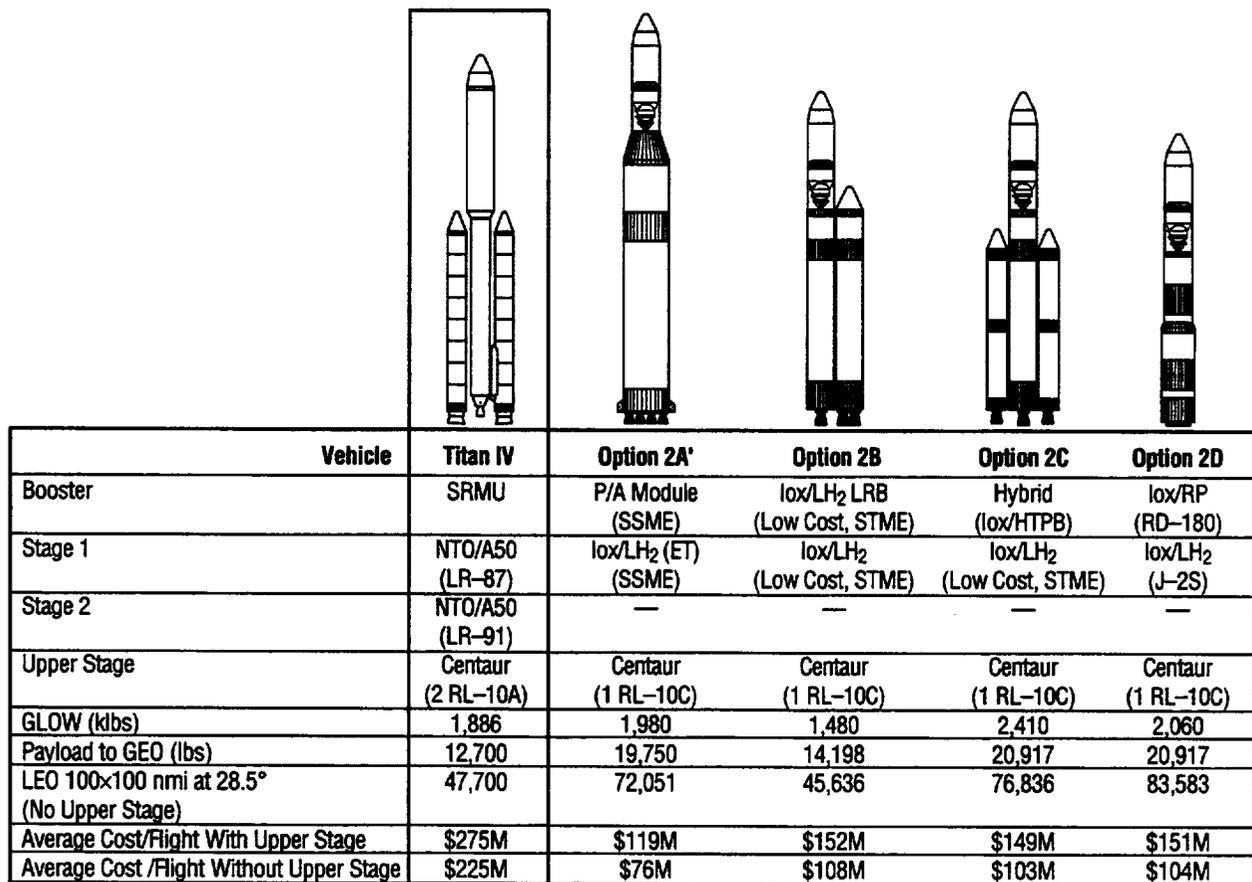


FIGURE 16.—20k launch vehicle comparison.

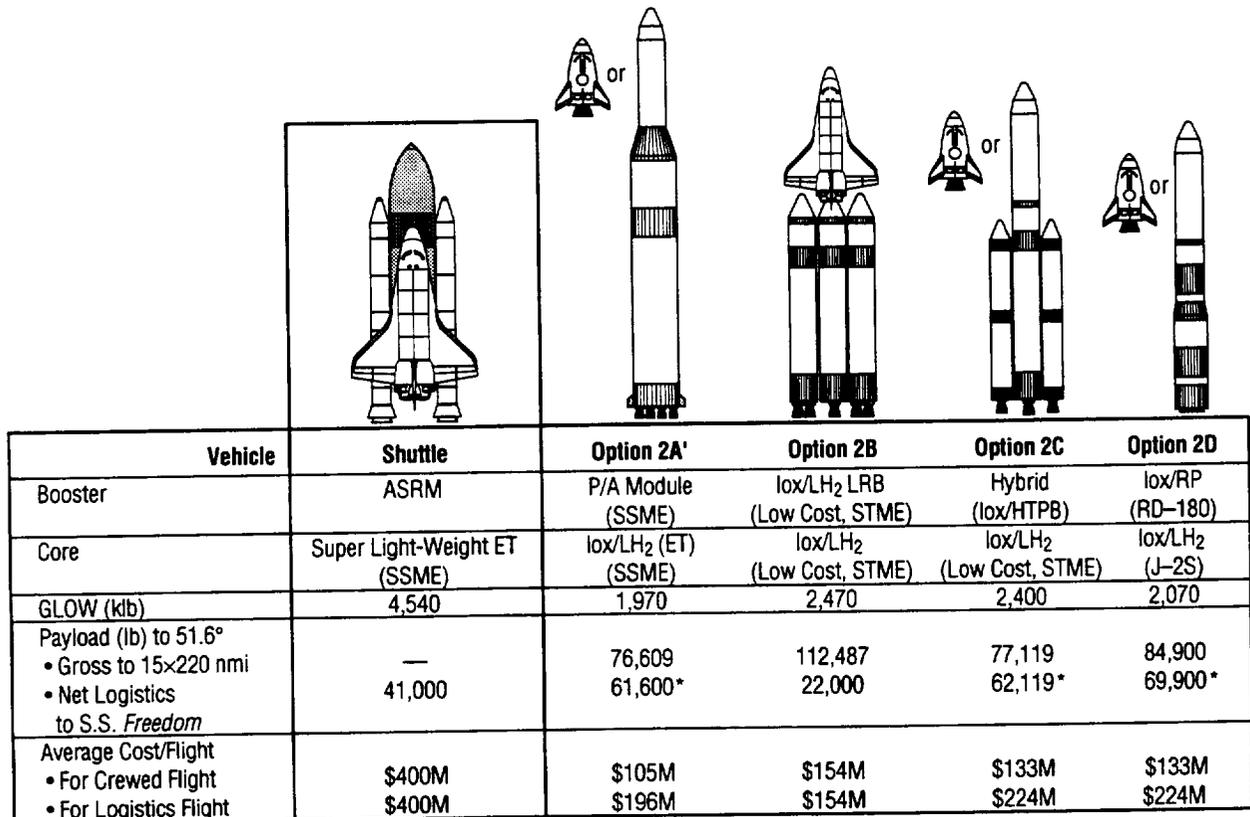


GLOW—Gross Lift-off Weight      SRMU—Solid Rocket Motor Upgraded

FIGURE 17.—Titan IV launch vehicle comparison.

### Space Station *Freedom* Logistics Vehicle Comparison

The Space Station *Freedom* crew logistics vehicle comparison is presented in figure 18. For Architecture 2A', the STS replacement is identical to the Titan replacement vehicle. For cargo applications, the launch vehicle, a Cargo Transfer Vehicle (CTV), shroud, and support equipment are mounted on the launch vehicle. For crew missions, the HL-42 is mounted on top of the core. The vehicle has a calculated reliability of 0.99. For Architecture 2B, the STS replacement vehicle is a parallel-burn core and with two liquid boosters. The CLV-P is flown uncrewed on cargo flights. For Architecture 2C, the Space Transportation System replacement is the same core with hybrid boosters used for Titan missions. For cargo missions, a CTV, shroud, and support equipment are utilized. The HL-42 flies on crew rotation missions. For Architecture 2D, the STS and TTV replacement vehicles are identical. For cargo missions, a CTV shroud and support equipment are utilized, while the HL-42 flies on crew rotation missions.



\* Net Payload to S.S. *Freedom* is reduced by 15,000 lb for ATV aerospace support equipment

FIGURE 18.—Space Station *Freedom* logistics vehicle comparison.

### Assessment and Down-Select

The assessment of the Option 2 architectures focused on the issue of logistics return. Full return capability drives cost by requiring a large payload systems (PLS) capability (CLV-P) that needs a 100k-pound launch vehicle or by requiring a high flight rate (20 per year) of an HL-42 PLS. Minimum logistics return capability allows for cost optimization of the architecture. For full return, Architecture 2B is the only option, while 2A', 2C, and 2D meet minimal return requirements. The cost trade can be summed up as comparing the minimal return lower recurring cost launcher/HL-42 and associated throw-away hardware (\$200M per year Space Station *Freedom* logistics and \$50M per flight for ATV) with the higher design, development, test, and evaluation/recurring cost of the 100k-pound launcher/CLV-P.

## Space Station Logistics

Current plans call for over 200k pounds of Space Station *Freedom* logistics to be delivered annually. The actual logistics mass, including sub-element packaging but excluding carriers is approximately 150k pounds per year. However, the central issue relative to access to space is the return mass. The current baseline, excluding logistics carriers, is 127k pounds. Analysis conducted by Langley Research Center (LaRC) has shown that the baseline return might be lowered from 127k pounds to 65k pounds by judicious return of spares, user, and crew systems.

The 65k return requirement consists of the three categories (crew systems, users, and spares). Each category was examined with LaRC and a return rationale was developed that emphasized the return of user payloads. All spares/maintenance were disposed along with five crew systems racks. The full complement of nine EVA suits would be returned. The result is that approximately 22k pounds of logistics would be returned. This would require three HL-42 flights per year for return mass. The acceptability of this level of return (approximately 15 percent of delivered mass) represents an issue that should be addressed in the final Space Station *Freedom* logistics scenario.

## Space Station *Freedom* Logistics Manifesting

A typical yearly Space Station *Freedom* manifest for Architecture 2D is shown in figure 19. The eight flights deliver the required up-logistics and use the HL-42 for crew rotation and selected logistics returns. Propulsion module (PM) propellant (7k pounds twice per year) is delivered. Every five years, the full PM would be delivered (nine total flights) to replace life limited hardware. Modified logistics carriers—six-bay pressurized logistics module (PLM) and 150-percent length unpressurized logistics carrier (ULC)—were needed to achieve this yearly Space Station *Freedom* logistics support. Finally, this manifest returned the 78 middeck lockers, extravehicular activity suits, and approximately 65 percent of the user pressurized racks. The 2.8k pounds of user unpressurized logistics were not returned.

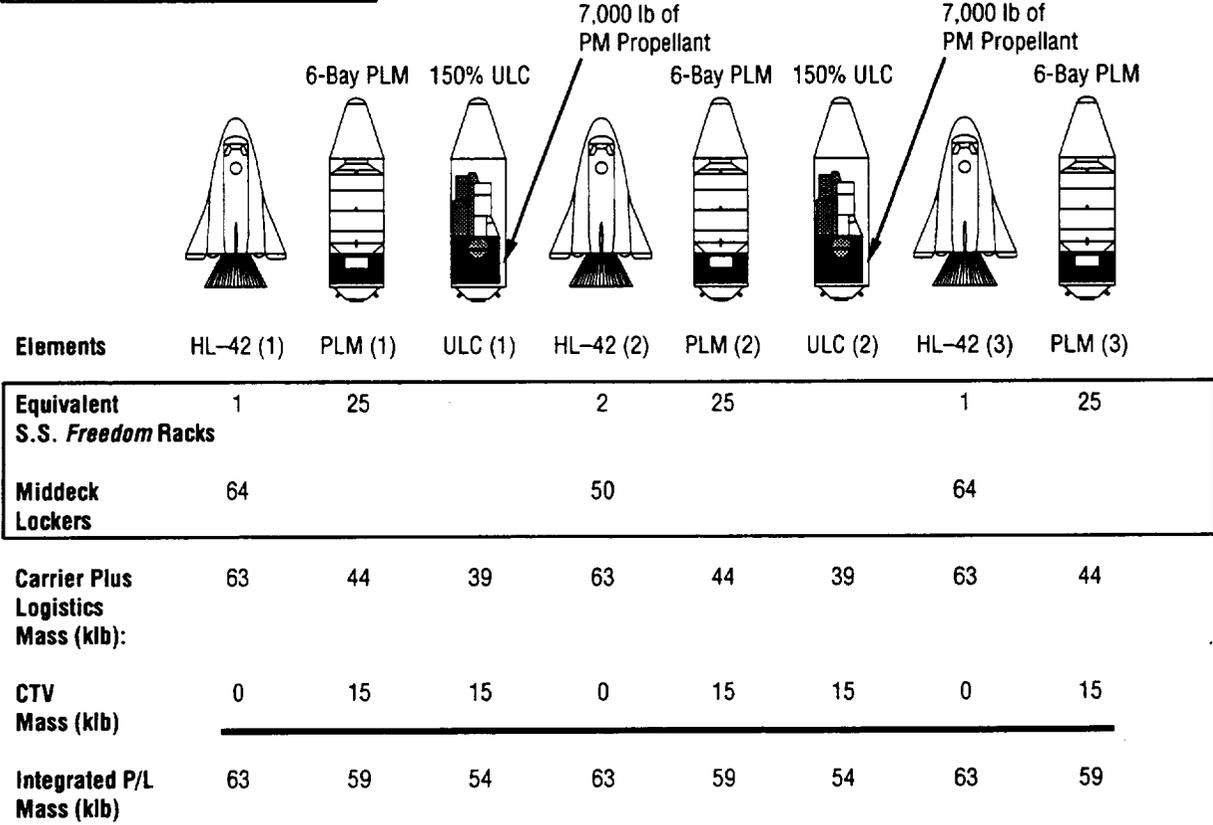
## Architecture Elements

The separation of crew and cargo has been studied by NASA for the past several years. The primary focus was to minimize crew exposure by not flying a crewed vehicle, thus eliminating crew system constraints for cargo-only missions. Personnel launch systems (PLS) vehicles tended to be small vehicles having very limited cargo capability. Designs varied from parachute recovery concepts (Biconic and Spacecab) to precision (runway) landers (HL-20 and HL-42). Cargo transfer and return (CTRV) vehicle designs ranged from vehicles capable of cargo capacity similar to the orbiter (medium CTRV, winged CTRV, and vertical lander) to smaller concepts (e.g., Spacecab, Caboose, integral CTRV). The CTRV concepts included both vehicles recovered by parachutes (medium CTRV, Spacecab, and Caboose) to precision lander (winged CTRV and vertical lander). Additionally, some design concepts combined crew and cargo (crew logistics vehicle (CLV)) were also investigated. The concepts were scaled versions of the current orbiter. Early in this study, it was recognized that precision landers were preferable for higher reliability and minimizing operations cost. This down-selection of concepts eliminated all parachute landing and reduced the number of PLS concepts from nine to three (HL-20, HL-42, and CLV) and CTRV concepts from 10 to three (Winged CTRV, HL-42, and CLV).

## Personnel Launch System

The down-selection process was derived from the Option 2 mission requirements and from design issues that surfaced during the study. Precision lander (runway landing) concepts were selected over parachute landing concepts to reduce the operations costs associated with parachute landing concepts. Powered vertical landing vehicles were not selected, based on risk. Smaller, less efficient crew/cargo vehicle concepts were eliminated in favor of the best

**Reusable PM Steady-State Logistics**



- During steady-state station operations ~14,000 lb of propulsion module propellant is delivered each year on two ULC flights.

Current estimate yearly logistics = 178 middeck lockers, 79 racks, 3 fluid carriers, 4 dry carriers, cargo, and propellant = 150k lb.

**FIGURE 19.—Steady State Space Station Freedom delivery/return using HL-42 plus ELV.**

combination for separate crew cargo (the HL-20 and CTRV combination) and the best two concepts for combined crew/cargo (the HL-42 and CLV-P concepts). Final selection was based on a greatly reduced cargo return requirement from Space Station, which enabled the crew/cargo HL-42 concept to meet the Option 2 mission requirements at a significantly reduced cost.

**Crew Logistics Vehicle**

The CLV-P class of spacecraft evolved based on: (1) The Space Station requirements, and (2) maximizing Shuttle heritage while upgrading systems to reflect today's technologies. The fundamental requirements to limit design, development, test, and evaluation cost resulted in the common airframe approach. A scaled version of the current orbiter minimized vehicle cross section, while still allowing accommodation of a Space Station propulsion module and a wing loading not to exceed the current orbiter wing loading for landing speed considerations. The CLV-P is a 70-percent scaled orbiter vehicle with a gross mass of 106,800 pounds, as shown in figure 20.

## Vehicle Design

The basic vehicle structure is aluminum, with the rudder, speed brake, and body flap constructed of advanced carbon-carbon (ACC). The thermal protection system includes blankets, TUF1-coated tiles, and ACC for the nose cap and wing leading edges. An integrated orbital maneuvering system and reaction control system was selected using liquid oxygen and a hydrocarbon fuel such as ethanol. Electro-mechanical actuators are used for aerosurface control, landing gear actuation, braking, and nose-wheel steering. Electrical power is obtained from long-life fuel cells for base power and high-power density fuel cells for electromechanical actuator power. The avionics architecture employs an integrated flight management unit with an inertial navigation system (INS), global positioning system, radar altimeter, and an air data system.

### Weight Estimate

<b>CLV-P (Pressurized Configuration)</b>	
Structure	24,447
TPS	12,627
Propulsion	2,373
Electric Power	6,430
Control	1,368
Avionics	2,021
Environment Control	6,693
Other	4,116
Growth	9,011
<b>Dry Weight</b>	<b>69,085</b>
<b>Consumables and Payload</b>	
Propellant	8,975
NonPropellant	2,136
Noncargo Prov.	7,192
Cargo	17,000
<b>Gross Weight</b>	<b>104,387</b>
Launch Vehicle Adapter	1,720
<b>Total Launch Weight</b>	<b>106,107</b>

Inert (59% scale)  
Gross (62% scale)

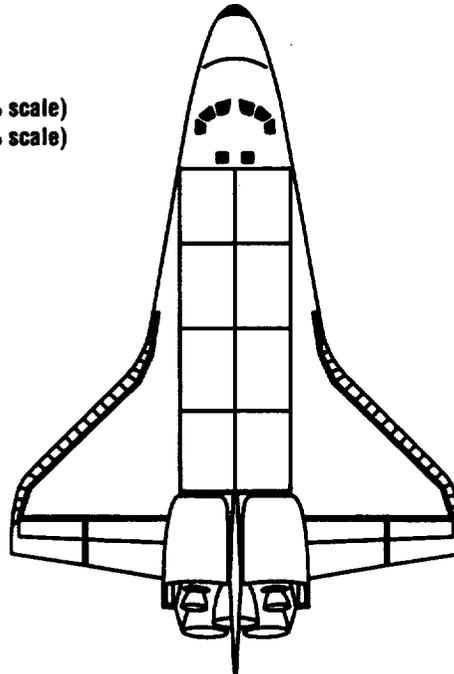


FIGURE 20.—CLV-P design.

## Mission Analysis and Aborts

A detailed mission analysis was completed resulting in a mission timeline, required delta-v and cross range, and landing opportunities. The nominal crew logistics vehicle mission will last 4 days, 20 hours from launch to landing, allowing some 99 hours docked to the Station. The on-orbit maneuvering propellant budget was sized for a delta-v of 844.6 fps. With weather alternate landing sites at Edwards Air Force Base and White Sands, the minimum cross range required for a nominal mission is 306 nautical miles. Abort capability is provided through ejection seats for low-altitude aborts and intact abort capability through the remainder of the ascent.

## HL-42

The HL-42 design stems directly from the HL-20 lifting body vehicle concept under study since 1983 at Langley Research Center. It is a 42 percent dimensional scale-up of the HL-20, and retains key design and operational features of the HL-20 design. The applicable HL-20 design data base includes extensive NASA aerodynamic, flight simulation and abort, and human-factors research, as well as results of contracted studies with Rockwell, Lockheed, and Boeing in defining efficient manufacturing and operations design.

## Vehicle Design

The HL-42, shown in figure 21 is a reusable lifting-body spacecraft with launch escape motors (for aborts) attached to the expendable launch vehicle adapter at the base of the HL-42.

The core of the HL-42 design is an aluminum, cylindrical, pressurized cabin that contains the crew and/or cargo. It has ingress/egress hatches at the top and rear of the cabin. Docking at the Space Station occurs at the rear of the HL-42. A 53-inch Space Station hatch permits loading and unloading of cargo as large as Space Station racks. Extending from the pressurized cabin are frame extensions that support the lower heat shield structure and define subsystem bays. A multipiece titanium heat shield structure defines the underside of the HL-42, with the Thermal Protection System (TUFI tiles) bonded directly to the titanium. The upper surface is composed of aluminum honeycomb removable panels that define the required aerodynamic shape and allow access to the subsystems located in the unpressurized bay areas. AFRSI thermal protection system is bonded directly to these panels. The titanium fins have direct bond thermal protection system (TUFI and FRSI) with the addition of advanced carbon-carbon for the higher heating leading edges. The vehicle nosecap is also made of advanced carbon-carbon.

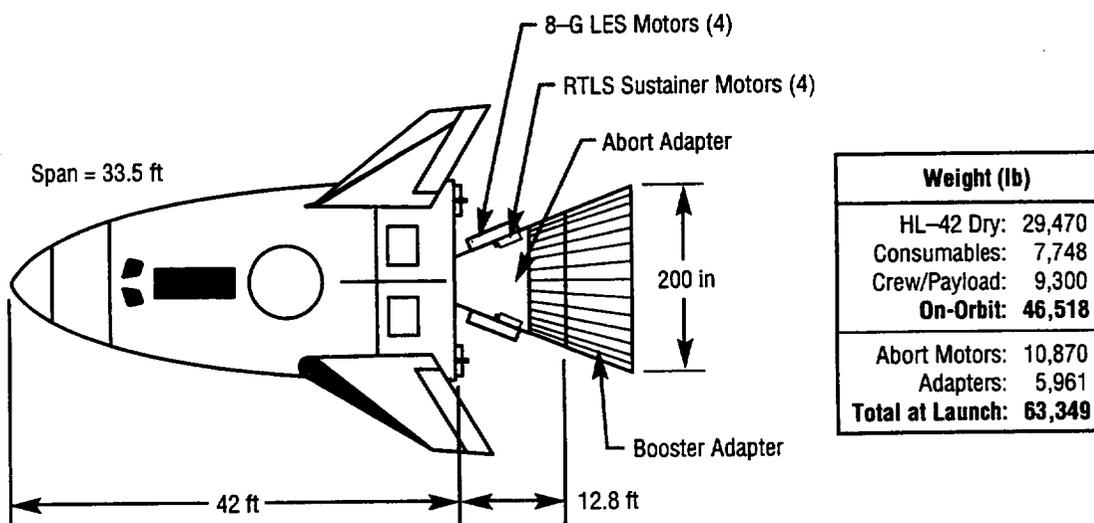


FIGURE 21.—HL-42 design.

Flight control consists of seven moving surfaces—four body flaps, two elevons on the large fins, and an all-moving center vertical fin. Control movement is effected using electro-mechanical actuators. Spacecraft power is supplied by hydrogen-oxygen fuel cells with limited emergency power backup provided using rechargeable silver-zinc batteries. The HL-42 propulsion consists of a methane (CH<sub>4</sub>) liquid oxygen orbital maneuvering system and reaction control subsystem for multiaxis attitude control on orbit and during entry. The CH<sub>4</sub>-liquid oxygen system was selected to delete hypergolic propellants and decrease operations cost.

### Mission Analysis and Aborts

The HL-42 spacecraft is launched by an expendable booster into a 15 by 220 nautical mile injection orbit inclined at 51.6 degrees. The orbital maneuvering system capability is 950 feet per second, consistent with maneuvers required to transfer to a 220 nautical mile Space Station orbit, circularization, rendezvous, and deorbit. Various combinations of crew and cargo (Space Station racks, early/late access lockers, and extended memory unit suits) may be carried by HL-42 in the pressurized cabin volume.

Crew safety and intact recovery are two aspects of abort addressed by the HL-42 design. The launch escape motors located on the launch vehicle adapter provide a high-thrust impulse to rapidly distance the HL-42 from a catastrophic booster event. While the HL-42 is on the launch pad and during the first 60 seconds of ascent, these abort motors provide for a return-to-launch site (RTL) capability and an intact runway landing. Some booster options also provide additional return-to-launch site capability beyond this initial period. Also, limited transatlantic (TAL) and abort-to-orbit (ATO) options exist near the end of the ascent-powered trajectory. However, for a significant portion of the ascent, with some architectures, the abort mode may result in an ocean ditching using emergency parachutes on board the HL-42. Under these conditions it is assumed the vehicle is expendable (not refurbished if recovered). Based on the flight rate, this event is estimated to occur only once in the mission model, with this vehicle attrition accounted for in the fleet sizing.

### **Cargo Transfer Vehicle**

The nominal transfer vehicle reference mission is to provide uncrewed logistics resupply to the Space Station and to destructively reenter with or without trash from the Station. The transfer vehicle must also provide the capability to deliver replacement modules to the Space Station and to destructively reenter excess module hardware. A transfer vehicle function is required in Option 2 architectures 2A', 2C, and 2D as the prime method of Space Station logistics delivery as well as replacement module delivery. In Architecture 2B, the transfer vehicle function is required only for module replacement/disposal.

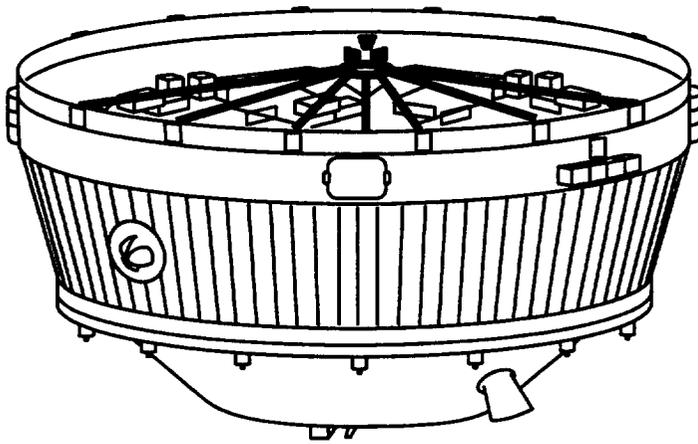
Existing and future spacecraft (both foreign and domestic) with potential for use as transfer vehicles were assessed. Three candidate systems met the mission requirements: U.S. Cargo Transfer Vehicle (CTV from the National Launch System baseline design), European Automated Transfer Vehicle (ATV), and the Russian Salyut Space Tug. Detailed information was assembled for both the U.S. CTV and the ATV designs. Salyut Space Tug information was inadequate for this study.

Comparative analysis of the U.S. CTV and the ATV indicated that the systems were essentially equal in performance and per-flight costs. However, the ATV design, development, test, and evaluation costs are the responsibility of the Europeans, whereas the U.S. CTV design, development, test, and evaluation costs drive the peak funding requirements at the time when requirements are the highest due to personnel launch systems and launch vehicle development funding. In addition, the ATV provides an avenue for *quid pro quo* payment of part or all of the European share of the Space Station operations costs. Thus, the ATV (figure 22) was judged to be the most cost-effective way to satisfy the transfer vehicle function required by Option 2. Launch of the ATV from Kennedy Space Center using a U.S. launch vehicle was judged to be the most cost-effective way to use the ATV in all architectures for Option 2.

## **Operations**

### **Operations Ground Rules and Guidelines**

Johnson Space Center, Kennedy Space Center, Langley Research Center, and Marshall Space Flight Center jointly established ground rules and guidelines that are consistent with an operationally efficient launch system and reduced operations costs. In order to minimize ground operations costs, the following items were eliminated from design consideration: solid rocket motors as core and booster stages; hydraulics; and hydrazine/ $N_2O_4$  systems. An integrated health management system was baselined to accomplish ground test and checkout with minimum personnel time and in one to two shifts. All vehicle and payload elements would be delivered to the launch site in flight-ready condition, with no open work. Test and checkout procedures at the launch site that duplicate those operations accomplished at the manufacturing facility have been eliminated. A crew chief approach is implemented at the



Dry Weights by Subsystem		
	(kg)	(lb)
Propulsion	587	1,292
GN&C	112	246
DHS	68	150
Communications	46	101
Power Supply	262	576
Mechanisms	95	209
Thermal Control	40	88
Structure	516	1,136
ATV Dry Mass	1,726	3,798
Margin (10%)	172	378
ATV Dry Mass W/Margin	1,898	4,176

Propellant Budgets				
For Composite ATV/Cargo Mass	Propellant		Wet ATV	
	(kg)	(lb)	(kg)	(lb)
21 Metric Tons	2,983	6,563	4,881	10,738
25 Metric Tons	3,756	8,263	5,654	12,439

**FIGURE 22.—European Automated Transfer Vehicle.**

launch site and the responsible launch site system/subsystem engineer provides the quality assurance sign-off for the systems. After initial operating capability (IOC), only “make-safe” and “make-it-work” design changes would be implemented. A block upgrade philosophy will be implemented to account for obsolescence and for cost reduction changes to the fleet.

Significant programmatic ground rules are: NASA operations support center exists only at mission control; ascent monitoring is accomplished at the launch site, with hand-over to mission control at payload separation; after initial operating capability, all government project/program support is at the launch site by one organization and the sustaining engineering is at the launch site; there is one logistics system for all elements; and configuration control is highly automated.

Significant portions of mission operations will be accomplished through the use of automatic systems. Launch, ascent, on-orbit operations, entry, and landing are automated and require no crew intervention, thus reducing cost by eliminating major requirements for facilities and crew training. Payload interfaces and procedures, mission planning, mission manifesting and premission products are simplified and standardized. Ground management of onboard systems will be reduced by automation and onboard vehicle health management. Trajectory and navigation management are decreased by using the Global Positioning Satellite system.

#### **Ground Operations**

All Option 2 vehicles will use the integrate/transfer/ launch (ITL) method of processing. The launch vehicle is vertically assembled and interfaces checked in the Vehicle Assembly Building (VAB). Once assembled, all systems will be functionally checked by an onboard autonomous test of the mechanical and fluid system, as well as electronic systems. Crewed spacecraft are prepared for flight in one of the Orbiter Processing Facilities (OPF) and transferred to the VAB for mating with the launch vehicle. Both LC39 pads will be modified to conduct Option 2 launches.

Adoption of the "ready for flight" approach to launch operations for the boosters effectively reduces the size of each option's launch crew; however, flight readiness testing and attendant cost must be accounted for under manufacturing. The "ready for flight" requires delivery of a "clean vehicle" with no open discrepancies or modifications. Additional staff reductions were realized by applying commercial support to hands-on personnel ratios. Commercial ratios are on the order of three-to-one compared to more than six-to-one for today's Shuttle. As the number of people were reduced through lower support ratios and less testing, so were the number of facilities necessary to house them.

Option 2 decreases the current number of facilities and requires no new facilities. Decreasing the number of facilities carries with it a very significant cost reduction. Not only are facilities reduced because of lower staffing levels and less testing, but they are further reduced by the fact that none of the families in the option use solid motors. Without solid motors, the entire Vehicle Assembly Building can be used to house people and conduct parallel processing. Seven solid motor buildings and more than 70 trailers and boxcars would be closed.

The most logical launch site to modify for a 20k vehicle is Complex 40 and its Vertical Integration Facility (VIF). Although no formal or informal agreement with the U.S. Air Force exist for Option 2, this location is ideal since it is an integrate, transfer, and launch layout similar to the Kennedy Space Center and meets Air Force requirements.

### **Mission Operations**

The proposed flight control and monitoring systems for the vehicles of the Option 2 architecture offer a unique opportunity to significantly change the current procedures for conducting mission operations. These changes must be given serious consideration in order to significantly reduce the operational life cycle cost of today's flight systems. It is believed that the technology of the proposed systems will be available during the development phase of the flight vehicles.

Primarily, it is the incorporation of internal vehicle health monitoring and control systems and the Global Positioning System that gives the capability to revise current mission operations procedures. Internal vehicle health monitoring and control systems are practical because of the technology advances in onboard computer systems. The Global Positioning Satellite is a proven system that provides instantaneous information on the position and attitude of the vehicle. This information revolutionizes the navigation and guidance processes for space vehicles. With the advent of these new technologies, the roles of flight crews and controllers can be significantly reduced.

The Option 2 flight scenario assumes that the Kennedy Space Center will be responsible for the flight of the expendable booster systems. Flight monitoring by the Johnson Space Center occurs when the vehicle has separated from the booster system (generally occurs at orbital insertion). Autonomous systems that had targeted the booster to the separation point would transfer control to the orbital vehicle's autonomous system. This system would calculate the orbital insertion and steer the vehicle to that position. The vehicle would then proceed to the next pre-defined phase of the mission. This sequence would continue until all the mission events had been completed. Ground monitors will have the capability to terminate any phase and re-initialize the autonomous flight system with new instructions.

The mission operations would require two facilities: a mission control center and a central simulation facility. These facilities will be designed to support a minimum of 12 flights per year. Design should provide for flight rate increase without major interference with current operations. The mission control center would not be responsible for payload operations. Only 10 to 12 console monitoring and control positions would be required. No requirements for real-time multipurpose support rooms have been identified. The mission control center would not be used for dedicated training. All training would be conducted in the central simulation facility. Training facilities should mirror flight control facilities for flight monitor

training. The training facilities would be used to verify pre-flight analyses. The primary mode of training would be computer based. No motion base, fixed based, or flight aircraft facilities will be required.

## Advanced Development Tasks Required

The selected technology/advanced development tasks that will enhance the next generation space launch system include tasks applicable to all architectures and tasks unique to an architecture. The generic tasks include: (1) avionics systems that can be upgraded, software that is automatically generated and validated, and the health management of in-flight functions; (2) electro-mechanical/hydraulic actuators and their electrical power driving and switching systems must be matured, with emphasis on the power supply systems; (3) advanced manufacturing to demonstrate and validate the most effective construction techniques for the expended cryo-propellant tanks (automatic welding and statistical process control (SPC) of components will reduce inspection, with significant reduction in cost and facilities without compromising reliability); (4) nontoxic orbital maneuvering subsystem/reaction control system propellant systems will increase the operational flexibility and decrease the associated costs by elimination of hazardous systems and the associated control of risks; and (5) a low-cost cryogenic upper stage engine, the number-one priority of the Space Transportation Advisory Committee, is required for all architectures. Modification to the existing Centaur and implementing an RL-10C engine, results in rapid development time and low program risk. A single-engine Centaur decreases costs, increases reliability, and increases operability. Application of advanced technology to the low-cost 50k-pound class engine also increases the capability of architectures.

The architecture-unique technology tasks include reusable propulsion/avionics modules (Architecture 2A') to substantially reduce launch costs. Propulsion/avionics modules package the costliest vehicle elements (main engines, auxiliary subsystem's power elements, main propulsion feedline elements, auxiliary propulsion subsystem, the thrust structure, and vehicle flight avionics systems) to be recovered in a dry condition and with minimum refurbishment. Hybrid motors (Architecture 2C) offer increased safety, low cost, operational flexibility, and an environmentally "friendly" propulsion. The technology effort is to mature and demonstrate hybrid propulsion technology to provide an adequate technology base and U.S. manufacturing infrastructure for U.S. commercial expendable launch vehicle competitiveness. A low-cost hydrogen fuel booster engine (Architectures 2B and 2C) using term-advanced technologies will have low development costs, rapid development time, and low program risk. The continuation of the space transportation main engine is required to retain the capability to transition to Option 2 in 2002.

## Costs

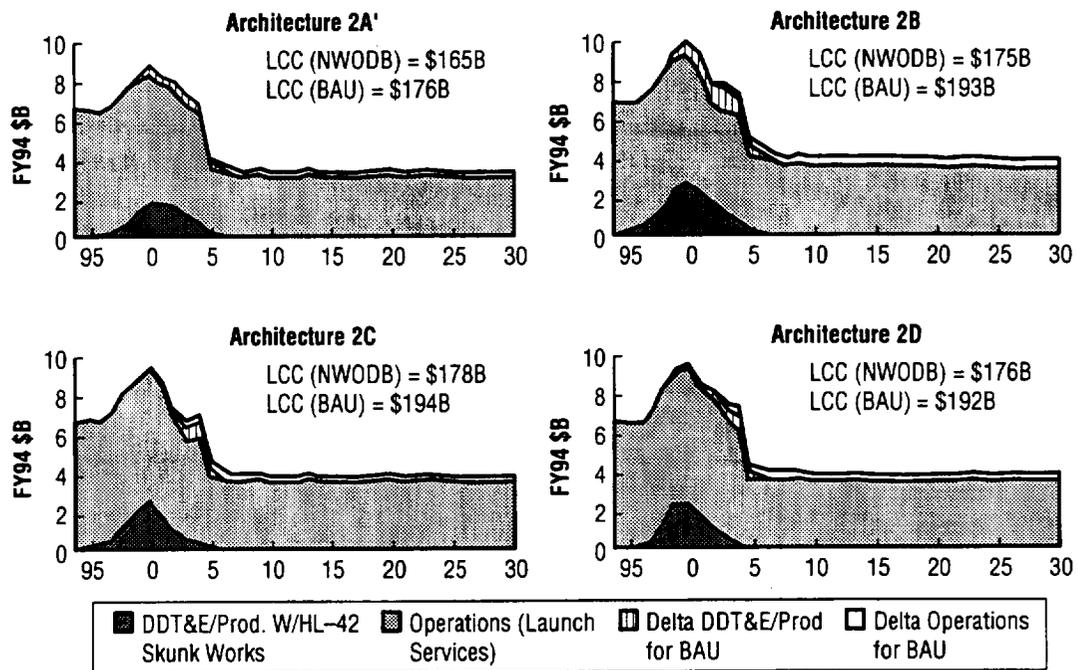
Design, development, test, and evaluation, production, and operations costs have been estimated over the life of the program. All transportation costs that are required to launch NASA and Department of Defense payloads over the 1994 through 2030 time period have been included, with the exceptions noted in the ground rules listed below. Although new and innovative ways of doing business, compared to the traditional ways NASA programs have been managed in the past, have been identified, their cost impact has not been fully qualified or validated. The development of the HL-42 and the CLV-P could use a "Skunk Works" type approach. This approach has been used successfully in major military programs such as the Hercules, U-2, and SR-71. In a study conducted on the HL-20 payload system by the Langley Research Center and Lockheed, it was determined that significant savings could be achieved using this approach. Based on those results, the new approach for the HL-42/CLV-P could yield reductions as high as 40-45 percent in the total spacecraft development and production cost estimates, compared to the traditional "business-as-usual" estimates.

These costing ground rules were followed:

- All costs are included with the following exceptions:
  - Civil service salaries and travel, and research operations support (ROS)
  - Pre-planned product improvement after the year 2000
  - Commercial flights.
- Business as usual and new ways of doing business are included. The latter is characterized by:
  - “Skunk Works” development for HL-42 and CLV-P (firm requirements, single management authority, small technical staff, customers on site, contractor inspections, limited outside access, timely funding, reports only important work, simple drawing release, rapid prototyping, etc.).
- Launch services are purchased from commercial suppliers (eliminated program office PMS and ETB overheads, and reduced operations cost by 10 percent).
- Architectures 2A', 2C, and 2D assume reduced Space Station *Freedom* return cargo. Architecture 2B is full return.
- Costs assume use of single-engine Centaur for upper stage, Titan IV shroud, and European Automated Transfer Vehicle.
- Cost estimates include reserves (30 percent of design, development, test, and evaluation, 20 percent of production), fee (10 percent), and program support (20 percent) except for production estimates based on actual current hardware production costs (i.e., external tank modules, Centaur upper stage, shrouds, and Automated Transfer Vehicle).
- Expendable launch vehicle infrastructure cost adjustments are Department of Defense estimates assuming 50 percent common, 25 percent Titan-unique, 12.5 percent Delta-unique and 12.5 percent Atlas-unique.
- Unreliability costs for all vehicles except the Space Transportation System, are based on actual experience on existing expendable launch vehicles and projected reliabilities for new vehicles. Payload losses (\$10k per pound) and reflight costs are included with HL-42 and CLV-P losses calculated for one vehicle each.
- Launch vehicle design, development, test, and evaluation costs are spread over 4 years using 60 percent cost/50 percent time Beta distribution. HL-42 and CLV-P are spread over 6 years.
- Production costs are spread over 3 years using 30 percent/40 percent/30 percent.
- Pre-development costs of 7 percent design, development, test, and evaluation are allocated at one percent for Phase A and six percent for Phase B.

The most cost-effective operations approach is for NASA to purchase commercial launch services similar to the current Delta and Atlas. This enables a healthy competitive environment with foreign suppliers and places payloads in orbit at the lowest cost. This approach would also reduce the government cost associated with project support, supporting the program office, providing a support contractor base, and maintaining the NASA facilities required to support the system over an extended operational period. Ten percent cost reduction in ground processing and mission operations can be realized by the purchase of launch services.

Figure 23 shows the design, development, test, and evaluation and operations cost profile over the 1994 to 2030 time period for Architectures 2A', 2B, 2C, and 2D. The cost estimates include the total government resources required to meet the planned NASA and Department of Defense mission models. The costs are plotted to show both the “business-as-usual” (BAU) estimates and a “new ways of doing business” (NWDB) estimate. In the latter, preliminary savings attributed to the “Skunk Works” type development and to the purchase of launch services are identified.



BAU = Business as usual  
 NWODB = New ways of doing business

FIGURE 23.—Total mission model cost spread.

## Assessment

Option 2 satisfies all national launch needs including commercial, national security, and civil missions. In addition, crew safety is improved by safe aborts for all mission phases, the elimination of solid rocket boosters, and reducing exposure from 8 to 3 flights per year. On uncrewed flights, mission reliabilities of greater than 0.98 are achievable. The Option 2 architectures significantly reduce life-cycle costs. For modest investments of \$7B–\$13B, annual operating costs can be reduced from \$6.7B (current) to \$3.7B–\$4.0B, resulting in total life-cycle cost savings of approximately \$50B. The architectures reduce technical and programmatic risk below prior programs by utilizing major elements/systems derived from current technology, large performance margins, evolution of existing propulsion systems, and management practices that minimize requirements change/growth. Environmental impacts are improved by the elimination of solids (except for small booster separation motors) and the elimination of hypergols (except for single-engine Centaur roll control).

The Option 2 architectures enhance the commercial competitiveness of launch vehicles by utilizing launch vehicle services if the new ways of doing business are adopted and providing competent capabilities in all payload ranges. Industrial capability is maintained and enhanced through near-term development efforts that can be phased to allow steady capability requirements (evolution path is 20k-cargo launch vehicle-crew transport launch vehicle). In comparison to existing systems, Option 2 offers other distinct advantages such as performance and reliability increases, operability increases, autonomous flight control, and growth capability to meet next generation space missions.

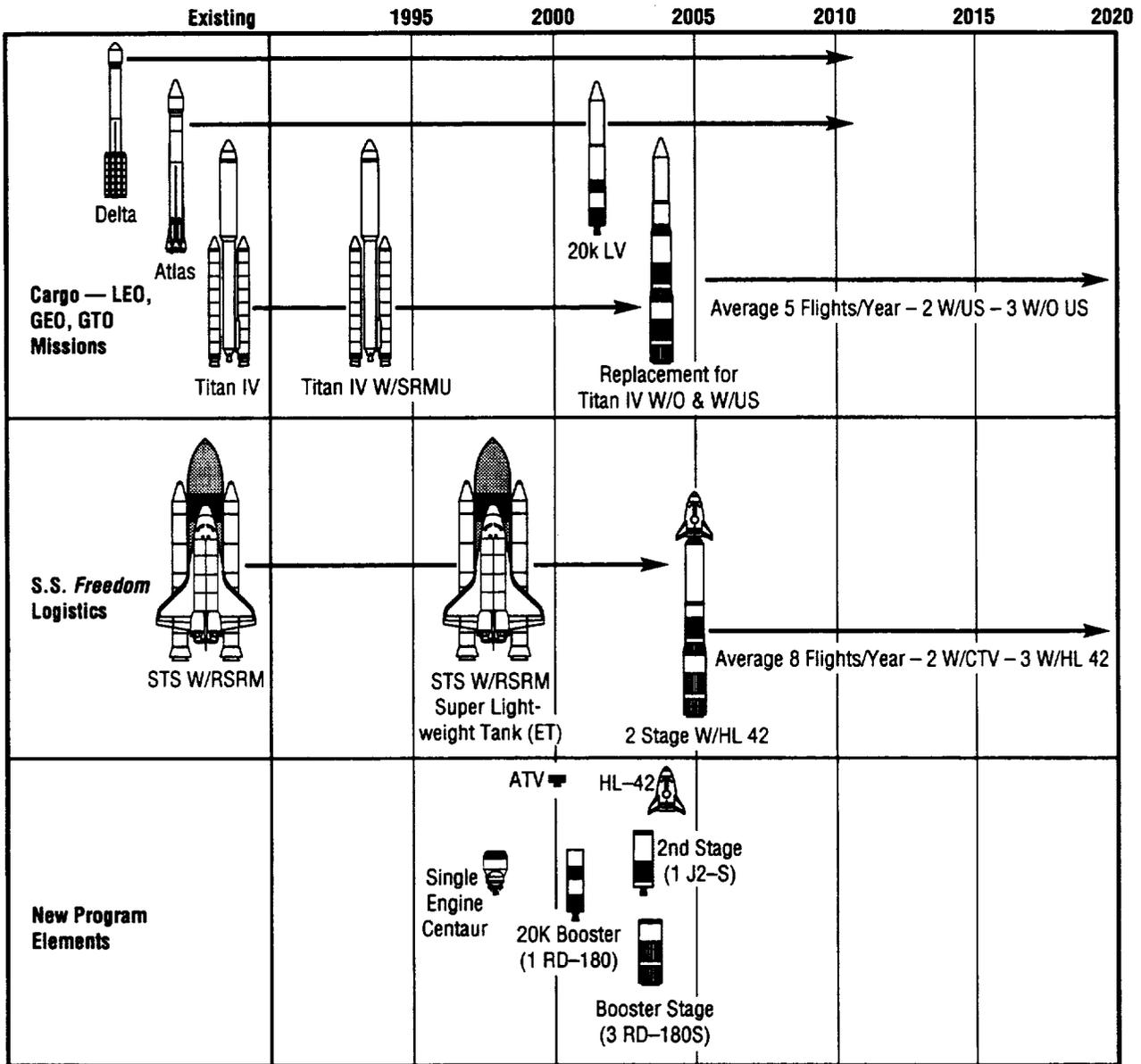


FIGURE 24.—Access to Space—Option 2D: Architecture 2D.

At the end of the study, a selection was made of alternative Architecture 2D as the most attractive overall. It is illustrated in figure 24, and its costs are shown in figure 25.

## Findings and Recommendations

Major findings include:

- Significant cost reductions, increased reliability, and increased crew safety can be accomplished relative to current systems.
- Operations cost reductions can be achieved with new designs, improved technology, and streamlined programatics (architecture effects are second order).

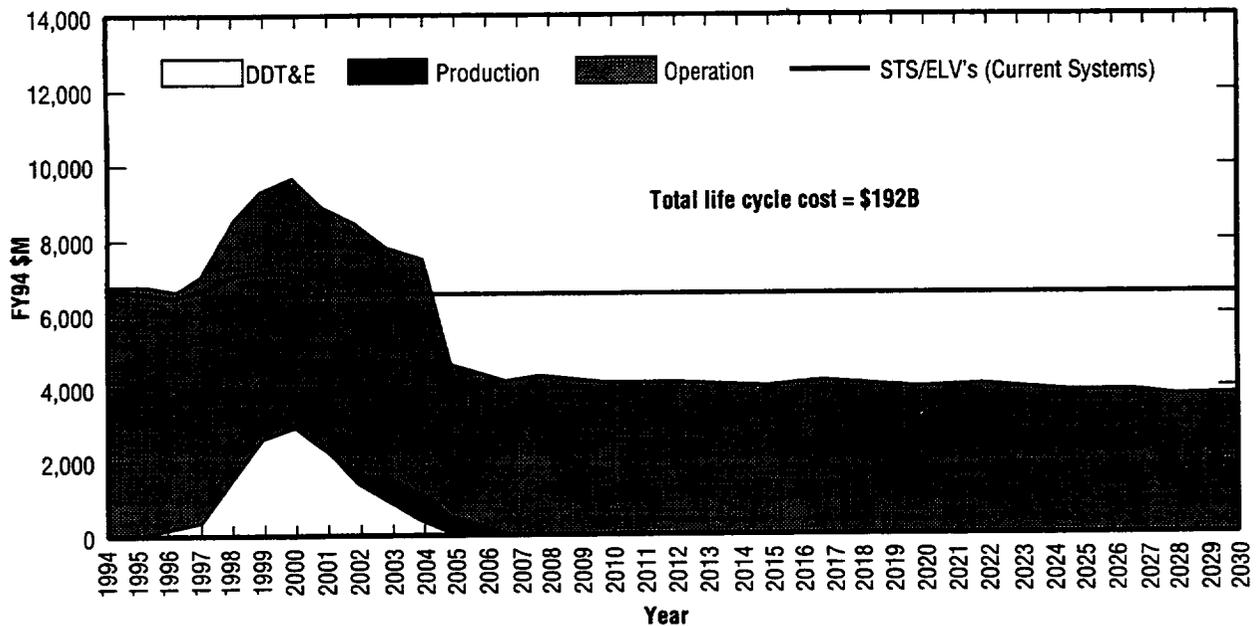


FIGURE 25.—Total mission model cost spread (Option 2D—BAU).

- \$40–\$50B life cycle cost savings require a \$7.5–\$13B investment for design, development, test, and evaluation.
- Life-cycle cost does not discriminate between architectures (eight percent variation).
- For Titan/Shuttle-class payloads, Architecture 2A' is the lowest cost; Architecture 2D is the lowest cost for 20k-class payloads.
- Propulsion system development time is a schedule driver.
- Increased performance capability relative to current systems allows for future growth in national launch requirements without compromising cost reductions.

In summary, the Option 2 recommendations are:

- The Space Station design should include the capability to accept crew/cargo from expendable launch vehicles.
- In order to improve crew safety, do not expose the crew to launch risk purely for cargo delivery and provide safe abort/escape for all ascent phases.
- In order to reduce cost, introduce conventional technology and reduce the complexity of existing systems, automate ground and flight systems for operability and reliability, implement second generation PLS with minimum crew flight rate, and utilize single low-cost commercial system to launch all Titan and Shuttle-class payloads.
- Develop an effective strategy to incrementally implement the next generation launch system with a range of capabilities, select an architecture where the propulsion elements lead the vehicle elements, consider ATV as the cargo transfer element, and support an aggressive technology/advanced development set of tasks until the next generation of systems for access to space are defined.
- Architecture 2D is the recommended architecture. Its costs are the lowest for the Atlas replacement vehicle, and it uses an existing engine to minimize research and development risk.

# Option 3 Team Analysis

## Approach

A joint NASA and Department of Defense team was assembled to develop a well-rounded approach to identifying the nation's space transportation architecture requirements and implementation alternatives. Vehicle concepts were designed for robust operational margins, instead of performance capability, through the use of various advanced technologies. However, a "culture change" in launch vehicle development, certification, and operations management must accompany the use of advanced technologies to leverage them to the greatest extent possible. Relevant government and industry concepts, operations models, and management philosophies were reviewed and considered by the team in its analysis.

## Architectural Alternatives Analyzed

On the basis of the 1990 Modified Civil Needs Data Base, approximately 90 percent of all future low-Earth orbit payloads are under 20k pounds and are under 20 feet in length. Delivery of these payloads (and their geosynchronous Earth orbit equivalent) was a primary driver in determining the payload size requirement of the advanced technology vehicle. There are approximately 18 satellite delivery missions in the 10k- to 20k-pound class each year (low-Earth orbit equivalent). A new liquid oxygen (lox)/liquid hydrogen (LH<sub>2</sub>) upper stage, approximately one-third the size of the Centaur, will be required to transfer the largest payloads from low-Earth orbit to geosynchronous-Earth orbit. The new vehicle is also required to support satellite servicing missions at a rate of approximately one every 3 years. An option for delivering Titan IV-class payloads was evaluated and vehicle concepts were developed to deliver a 45k-pound payload to low-Earth orbit. However, this was not baselined due to the small number of Titan-class flights per year (three), the uncertainty of their payload volume requirements post-2000, and because of the corresponding increase in vehicle size. Instead, such a vehicle is treated as an option.

A total of 150k pounds of Space Station resupply logistics are required to be delivered, and 125k pounds to be returned, by the vehicle each year, based on current requirements for Space Station permanently crewed capability. The Space Station payloads are transported using standard unpressurized logistics carriers and the minipressurized logistics module.

Based upon previous flight experience and state-of-the-art avionics, the Option 3 vehicle must be capable of autonomous flight operations. When required (e.g., servicing missions), the vehicle has the capability of being operated on-orbit by a two-person crew to enhance safety and perform nonstandard mission operations. Also, the vehicle must have the capability to transport an additional four Space Station crew members and the associated payloads that require late or early access.

Taking all domestic payload requirements into consideration, the advanced technology vehicle is configured with a 25,000 pound payload capability to a 220 nautical mile circular orbit inclined at 51.6 degrees. To meet this mission model, 39 flights per year, on average, will be required. The vehicle has a payload bay that is 15 feet in diameter and 30-feet long. An expendable launch vehicle of the Titan IV class will be used to meet the missions requiring a 40,000 to 50,000 pound payload capability. However, an option has been developed that uses a larger advanced technology vehicle to meet the all the requirements.

## Space Transportation Architecture

Figure 26 illustrates the recommended Option 3 architecture based on the mission requirements from section 2.1. The 30- and 45-foot payload bay vehicles are shown as alternatives A and B. Cargo and crewed missions are shown along with requirements for major new elements and the approximate time frame of their implementation. This architecture is generic, with the reusable launch vehicle icon shown in the figure representing several advanced technology launch system concepts evaluated.

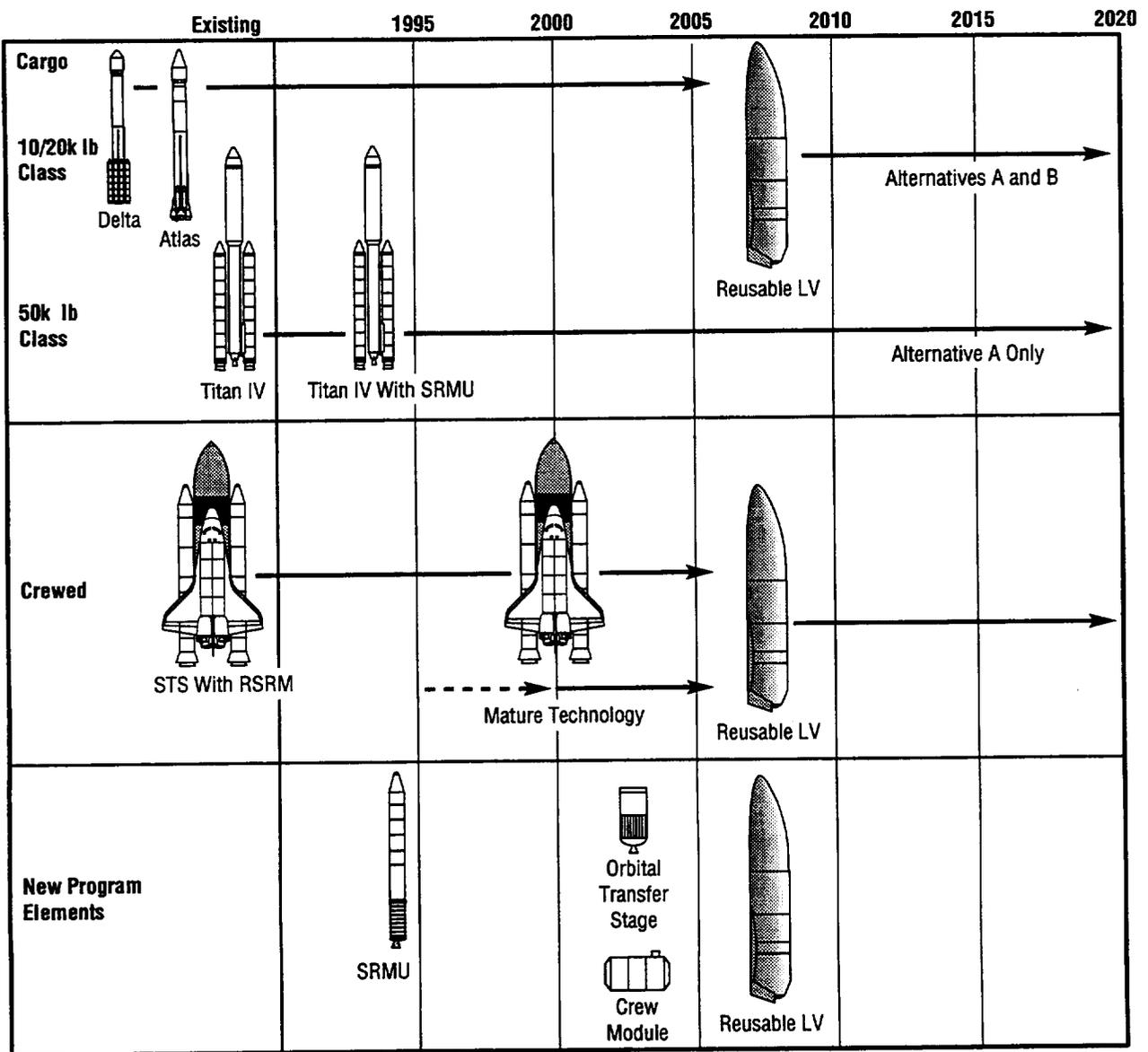


FIGURE 26.—Option 3 architecture.

### Vehicle Concept Options

Three launch vehicle concept design options have been chosen by the Option 3 team for engineering analysis and costing, as representative of the numerous fully-reusable vehicle concept possibilities. The concepts are:

- An all-rocket-powered single-stage-to-orbit (SSTO-R)
- A combination of air-breather plus rocket-powered single-stage-to-orbit (SSTO-A/R)
- A combination of air-breather plus rocket-powered two-stage-to-orbit (TSTO-A/R).

These three concepts have been identified because they represent the largest range of candidate vehicle options in terms of technology requirements for reusable launch systems, and because government studies were already in progress to evaluate these concepts at the initiation of this study. It is emphasized that these concepts are intended to serve as representative vehicles for technology and operations evaluations, and are not intended to serve as final concept recommendations. The use of advanced technologies is being considered to increase operability, margins, durability, and to enable full reusability.

## Major Features of Architectures

The three reference vehicle concepts were designed to an equivalent depth so that an “apples-to-apples” comparison could be made. They all had features that would enhance reliability, operability, and maintainability. These features include the following:

- One-time vehicle flight certification.
  - This requires building in increased margins over that used in the Space Shuttle design.
  - The Space Shuttle is essentially recertified after each flight.
  - The tests and inspections required for this greatly increase the ground processing time.
- Off-line payload processing.
  - To minimize the impact of the payload on the vehicle, it is required that the payload be processed separately from the vehicle and that the payload place minimum requirements on the vehicle.
  - The payload bay of the Space Shuttle is reconfigured for each flight, which again increases the ground processing time.
- Minimize serial processing.
  - To reduce the overall ground processing time, serial processes must be minimized.
- Durable thermal protection system.
  - Many programs are underway, e.g., at Langley Research Center and Ames Research Center, to develop a thermal protection system that is both more durable than the current thermal protection system used by the Space Shuttle and also requires less servicing between missions.
- Autonomous avionics.
  - The use of the Global Positioning System, coupled with the advances in electronics, makes this feasible using today’s technology.

Table 1 compares the key features of each vehicle.

**TABLE 1.—Reference vehicle comparisons**

Feature	SSTO (R)	SSTO (A/R)	TSTO (A/R) (Booster)	TSTO (A/R) (Orbiter)
Gross Mass (lb)	1,961,303	917,000	352,000	450,000
Dry Mass (lb)	159,500	239,000	252,000	52,000
Engine Type	RD-704 Class	Low-Speed Airbreather/ Ramjet/Scramjet & Linear Modular Aerospike Rocket	Turbofans/ Ramjets	P&W RL-200 (New Engine Development)
Lox Tank	Al/Li Integral/Circular	Al/Li Integral/Conformal	N/A	Al/Li Non-Integral
LH <sub>2</sub> Tank	Al/Li Integral/Circular	N/A	Graphite Composite Integral	Graphite Composite Integral
Slush Hydrogen Tank	N/A	Graphite Composite Integral/Conformal	N/A	N/A
Primary Structure	Graphite Composite	Graphite Composite	Graphite Composite	Graphite Composite
TPS	Passive AFRSI/TABI/ACC	Passive FRCI-12/TABI/ Carbon-SiC Active LH <sub>2</sub>	Passive TABI/TUFI	Passive TABI/TUFI
Aerosurface Controls	EMA	8,000 psia Hydraulics	8,000 psia Hydraulics	EMA
Aerosurfaces	ACC	TMC (With C/SiC Where Needed)	Ti H/C	ACC
Electrical Power Generation	Fuel Cells	Fuel Cells	Air Turbine	Fuel Cells

### Single-Stage-to-Orbit—All Rocket

The design philosophy of the reference single-stage-to-orbit all-rocket vehicle is to maximize the lessons learned from the Space Shuttle program and apply the minimum technology required to allow for an operationally efficient vehicle. These major design requirements, in addition to the characteristics identified previously, include the following:

- Eliminate downrange abort sites
- Eliminate hydraulics
- Eliminate hypergolic propellants
- Use evolutionary engines
- Use Al-Li for the LH<sub>2</sub> and lox tanks
- Use normal boiling point propellants
- Use simple circular cross-section fuselage and tanks
- Design propellant tanks for internal pressures similar to the Shuttle external tank.

The all-rocket-powered single-stage-to-orbit configuration is designed to take off vertically, like a standard launch vehicle, and land horizontally at mission completion, like the Space Shuttle. Two suboptions exist within this rocket option: (1) a vehicle based on seven lox/LH<sub>2</sub> engines evolved from the space shuttle main engine with equivalent performance characteristics, but designed for higher levels of operability and maintainability; and (2) a vehicle based on seven tripropellant (lox/RP/LH<sub>2</sub>) engines of the performance class of a single bell Russian RD-701 (i.e., RD-704). The RD-701 has component heritage from the RD-170 (Zenit and Energia booster engine) and RD-120 engines. The RD-701 drawings are 80 percent complete. This latter tripropellant option is illustrated in figure 27.

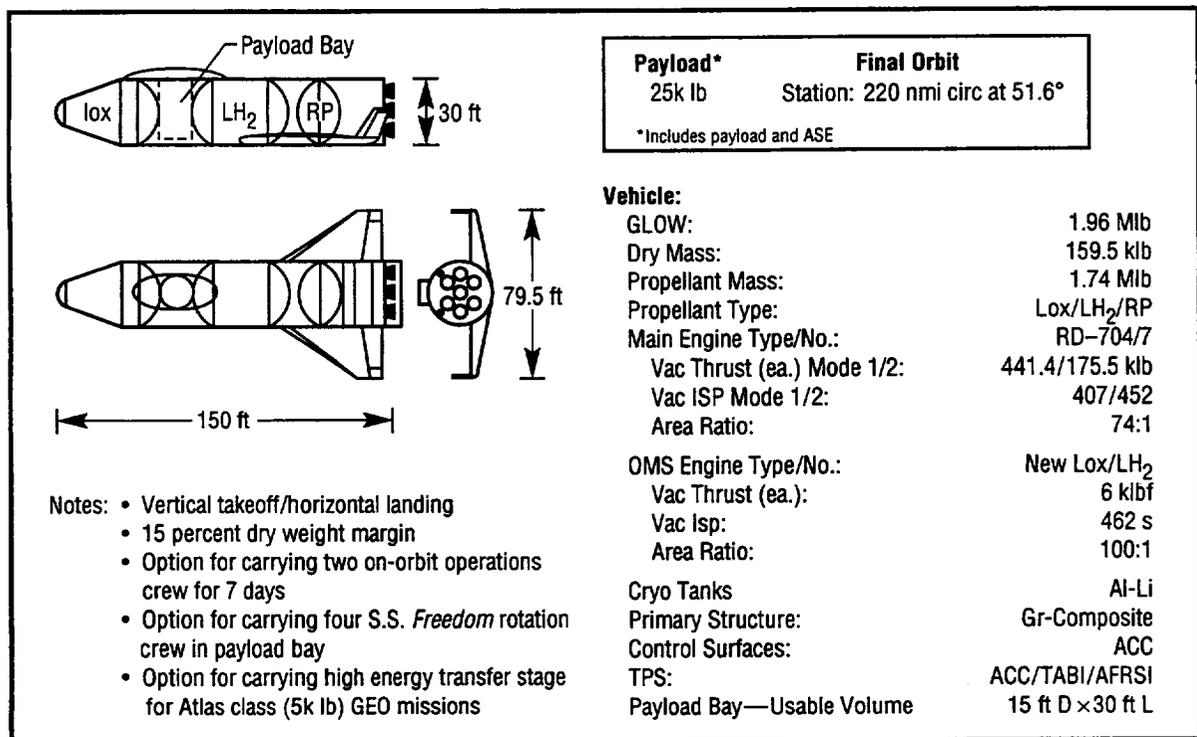


FIGURE 27.—Reference single-stage-to-orbit rocket.

In addition, after initial and preliminary discussions with the U.S. Air Force Space Command, it was determined that a 45-foot long cargo bay coupled with a 45k-pound payload capability to low-Earth orbit at the 28.5 degree inclination may allow the advanced technology vehicle to deliver the next generation of Titan IV payloads (scheduled to undergo a block change early in the next century). Because of the requirement for a third propellant tank (i.e., RP), the tripropellant option allows for a 15-foot diameter by 45-foot long cargo bay to be placed longitudinally in the vehicle.

The masses associated with the lox hydrogen and the tripropellant vehicle variants are shown in table 2, and the cost estimates in table 3.

TABLE 2.—*Vehicle masses*

	Lox/LH <sub>2</sub>	Tripropellant: 30-ft Bay
Dry Mass	233k lb	159k lb
Gross Mass	2.48M lb	1.96M lb

The weights of these vehicles can be reduced substantially by adopting graphite composites for the fuel tanks instead of aluminum-lithium. This is discussed under the Single-Stage-to-Orbit Feasibility section.

TABLE 3.—*Cost estimates for the single-stage-to-orbit rocket*

FY94 \$B	Lox/LH <sub>2</sub>	Tripropellant: 30-ft Bay
Technology	0.90	0.90
DDT&E	17.60	16.70
Annual Operations*	1.40	1.40

\* SSTO Vehicle and Associated Elements Only

### Single-Stage-to-Orbit—Air-Breather/Rocket Combination

Air-breathing/rocket-powered, single-stage-to-orbit, horizontal takeoff and landing (HTOL) aerospace planes are highly integrated systems with unprecedented levels of interdisciplinary interactions involving a broad spectrum of technologies. This type of vehicle has numerous design variables and can evolve to a robust, flexible machine using a highly optimized design process if the systems/disciplines are integrated synergistically and the appropriate technologies matured. Such a vehicle can provide routine access to orbit at reduced cost, increased operational flexibility (ground and flight), and reliability. Many of these attributes stem from the airplane characteristics of this vehicle, such as lifting body, air-breathing propulsion, horizontal takeoff and landing, and so forth. The single-stage-to-orbit air-breather/rocket combination is an airplane that goes into orbit and, as such, can be expected to accrue many of the desirable operational characteristics associated with contemporary high-performance aircraft. Specifically, they materialize through:

- Gradual step and check engine startup and shutdown
- Horizontal takeoff/abort capability
- Atmospheric abort with powered fly back
- Large launch window potential
- Launch offset capability
- Large cross range
- Subsonic and/or supersonic ferry capability with either SLH<sub>2</sub> or LH<sub>2</sub>
- Hypersonic cruise capability.

The air-breathing/rocket-powered single-stage-to-orbit configuration is designed to take off horizontally and land horizontally. The baseline propulsion system is derived from that being developed by the National Aerospace Plane (NASP) Program. The reference vehicle uses a special low-speed propulsion mode, ramjets, and supersonic combustion ramjets (scramjets) for primary propulsion along with lox/LH<sub>2</sub> rocket augmentation in the low and high speed regimes of the ascent trajectory. The reference vehicle has a gross lift-off mass of approximately 900,000 pounds and a dry mass of approximately 240,000 pounds. This concept is illustrated in figure 28.

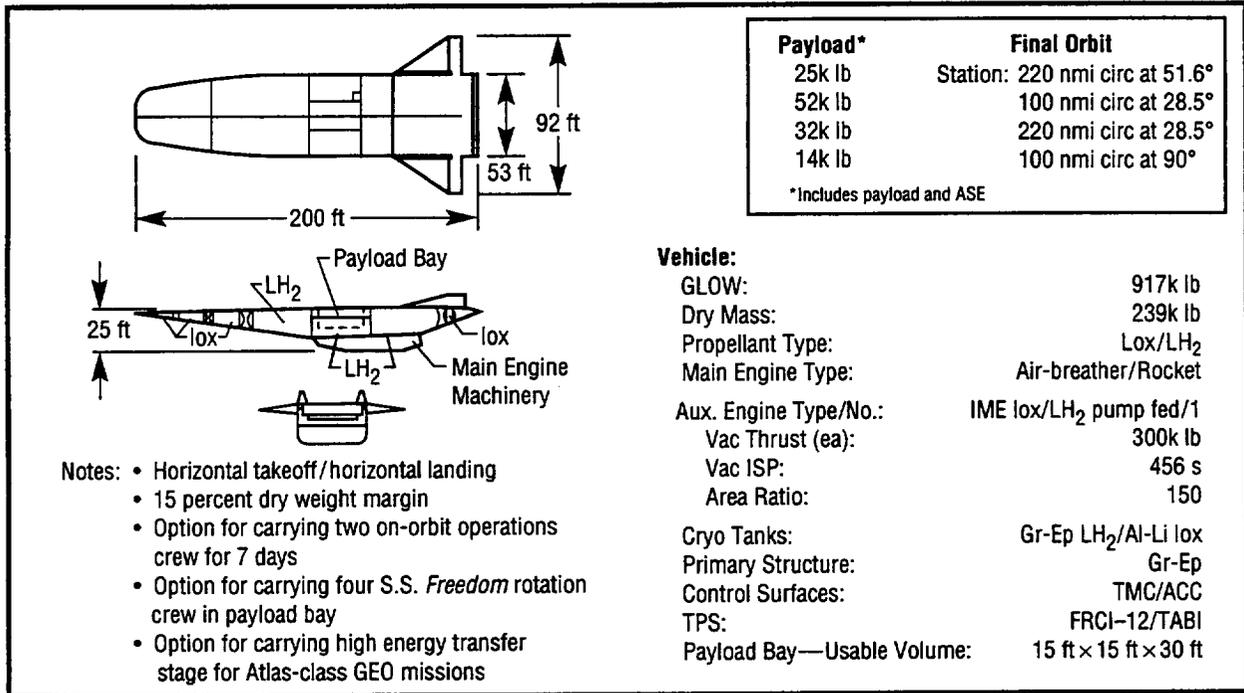


FIGURE 28.—Single-stage-to-orbit (air-breather/rocket) vehicle characteristics.

The cost estimates are given in table 4.

TABLE 4.—Cost estimates for the single-stage-to-orbit air-breather/rocket

	FY94 \$B
Technology	3.10
DDT&E	22.0
Annual Operations*	1.5

\* SSTO vehicle and associated elements only

### Two-Stage-to-Orbit—Air-Breather/Rocket Combination

The air-breather/rocket-powered two-stage-to-orbit configuration is designed to take off horizontally and land horizontally. The vehicle configuration consists of a booster vehicle and a piggyback orbiter vehicle. The booster propulsion system is a combination of turbofan jet engines and LH<sub>2</sub> fueled ramjets. The booster/orbiter staging velocity occurs at Mach 5. The orbiter is powered by four RL-200 class of rocket engines. The reference vehicle has a combined gross liftoff mass of approximately 800,000 pounds and a dry mass of approximately 250,000 pounds. This concept is illustrated in figure 29.

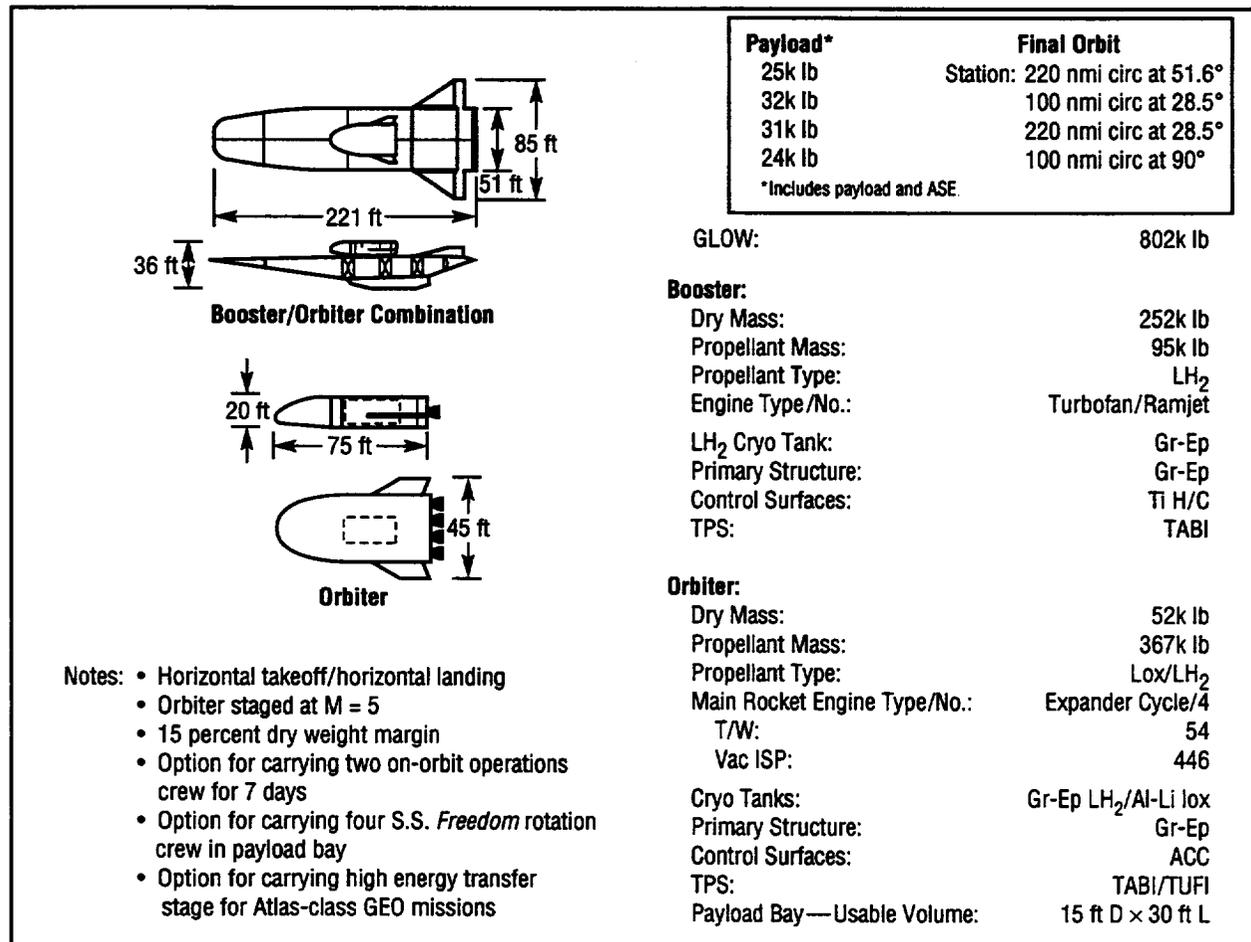


FIGURE 29.—Two-stage-to-orbit (air-breather/rocket) vehicle characteristics.

The cost estimates are shown in table 5.

TABLE 5.—Cost estimates for the two-stage-to-orbit air-breather/rocket

	FY94 \$B
Technology	1.20
DDT&E	26.80
Annual Operations*	1.45

\* SSTO vehicle and associated elements only

Key features of each vehicle are shown in table 1 and in figure 30 to allow direct comparison of the alternatives. These vehicles are representative of the concepts and none can be called an optimized design.

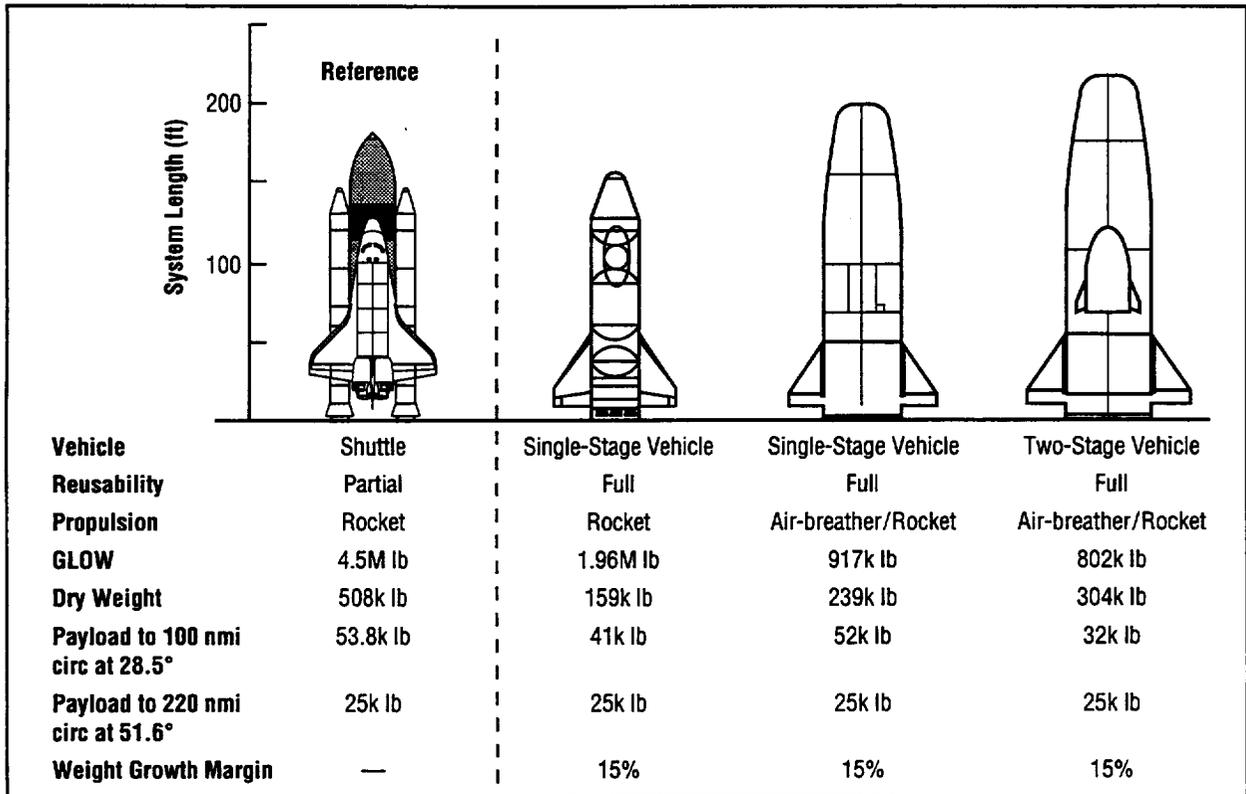


FIGURE 30.—Option 3: representative vehicle concepts.

### Assessment and Down-Select

All three vehicle concepts evaluated meet the payload delivery requirements set forth at the outset of the study. While the annual operations cost estimates are not a discriminator between the three options, there is a significant difference in the technology and development costs. Neither crew safety, vehicle reliability, impacts to the environment, nor degree of contribution to the industrial competitiveness of the nation appear to be discriminating factors between the three options.

While many significant advances in materials and propulsion related technologies have been made in the National Aerospace Plane Program in the past 8 years, several critical items remain to be developed. These include a ramjet/scramjet engine combination, slush hydrogen systems, and actively cooled engine and leading edge panels. This integrated system must also be overlaid on a requirement for an operable system. While the single-stage-to-orbit air-breather/rocket offers some unique capabilities, such as cruise, self-ferry, and offset launch, the combined technology and development cost estimate exceeds \$25B. The high costs and technology requirements make this an unfavorable option for future space access in the 2008 time frame.

The two-stage-to-orbit air-breathing rocket vehicle, while having many of the advantages of the single-stage-to-orbit air-breathing rocket vehicle, does not require the development of a scramjet and actively cooled panels. However, it does require the development of two dissimilar stages. While the two-stage-to-orbit air-breathing rocket has a lower technology cost than the single-stage-to-orbit air-breathing rocket (i.e., \$1.2B), the technology and development cost estimate is \$28B. The reduced technology requirements for the two-stage concept do not appear to offset the high development costs of this concept.

Therefore, the development of a single-stage-to-orbit all-rocket vehicle appears to be the best blend of near-term achievable technology and affordability for routine space access beginning in the 2008 time frame. Its combined technology and development cost is the lowest of the alternatives, projected at \$17.6–\$18.5B. It is an evolutionary, not revolutionary, path that relies on technologies mostly evolved over the past 20 years in the aerospace industry. However, it does require the maturation and demonstration of several key technologies. This is expected to require \$900M over 5 years.

The initial single-stage-to-orbit all-rocket reference concept, carried throughout the majority of the study, was based on seven Space Shuttle main engine-evolved engines. However, the use of a tripropellant engine (of the RD-704 class) provides for a significant reduction in overall vehicle dry mass (e.g., reduced development cost), as illustrated in figures 27 and 30. At the design reference point of 15 percent dry mass margin, the tripropellant vehicle dry mass is 32 percent lighter than the lox/LH<sub>2</sub> vehicle. Because of the requirement for a third propellant tank (i.e., RP), the tripropellant option also allows for a longitudinal, 15-foot diameter by 45-foot long cargo bay to be placed in the vehicle to meet Titan IV payload requirements. The addition of a third propellant (RP) does not appear to significantly affect the cost of operating the single-stage-to-orbit vehicle.

Because of the reduction in vehicle dry mass that allows the vehicle dry weight growth margin to be increased to 25–35 percent, reduced cost, and the potential for meeting Titan IV payload requirements, it is recommended that future studies focus on the development of a single-stage-to-orbit all-rocket vehicle based on a tripropellant engine of the RD-704 performance class.

## Details of Selected Architecture

The propulsion system for the reference vehicle is based on the Russian tripropellant RD-704 engine.

The single-stage-to-orbit all-rocket vehicle is a vertical take-off, horizontal landing, winged concept with a circular cross-section fuselage for structural efficiency. The payload bay is located between an aft LH<sub>2</sub> tank and a forward lox tank. The normal boiling point LH<sub>2</sub> and lox propellants are contained in integral, reusable cryogenic tanks constructed of aluminum-lithium material. An option exists to construct the fuel tanks of graphite-composite materials for extra margin. The capability for carrying a crew on missions that require human presence is provided by a crew module which is interchangeable with the cargo module, but the vehicle remains totally automated. The vehicle employs wing tip fin controllers for directional control. A standardized payload canister concept is used with common interfaces that allow off-line processing of payloads and rapid payload integration.

All nonpressurized primary structural materials are graphite composite, drawing on current airplane and rocket designs. The thermal protection system is composed of advanced carbon-carbon materials for the control surfaces, nose cap, and wing leading edge. The remaining areas of the wing and body are covered with advanced fully reusable surface insulation (AFRSI) where ascent/entry stagnation temperatures will be below 1,200 °F, or TABI where stagnation temperatures will be below 2,000 °F. Both AFRSI and TABI are blanket-type.

The main propulsion system for the single-stage-to-orbit all-rocket vehicle consists of seven tripropellant engines based on the RD-704 engine concept. Specifically, this is a

truncated, single-bell version of the RD-701. An alternative is to use three RD-701 engines, each with double bell. The design of the RD-701 is 80 percent complete, with drawings released for all but the main injector, preburner injector, and LH<sub>2</sub> turbopump. If selected, the RD-704 design responsibility is to be shared between NPO Energomash (Russia) and Pratt and Whitney. The RD-704 has a component design heritage from the RD-170, RD-120, XLR-129, and Space Shuttle Main Engine alternative turbopump development. The RD-704 engine specifications are given in table 6.

TABLE 6.—Engine specifications for the RD-704

Mode		1	2	Mode		1	2
• Propellants		LO <sub>2</sub> /LH <sub>2</sub> /RP-1	LO <sub>2</sub> /LH <sub>2</sub>	• Chamber Pressure (psia)		4,266	1,726
• Thrust (lb)	S.L.	386,140	N/A	• Area Ratio		74	
	Vac.	441,430	175,560	• Dimensions (in)	Dia.	70.1	
• Impulse (sec)	S.L.	356/351	N/A	(Single Bell)	Length	151	
(Nominal/Worst Case)	Vac.	407/401	452/450	• Throttleable (percent)		10-100	
• Weight (lb)			5,300	• Total Mass Flow Rate (lb/sec)		1,085	388
• Mixture Ratio (O/F)		4.28	6.0				

The single-stage-to-orbit all-rocket vehicle is designed to deliver and return 25,000 pounds of payload to the Space Station located in a 220 nautical miles circular orbit inclined at 51.6 degrees. In addition, the design includes enough additional propellant to provide a 5-minute launch window for Space Station rendezvous.

One major design issue is to provide for a safe recovery of the vehicle in the event of a loss of the thrust from one engine throughout ascent. The single-stage-to-orbit all-rocket vehicle meets this mission requirement by providing for the capability to return to the launch site in the event of the loss of an engine from lift-off to 206 seconds into the trajectory. The vehicle can fail-safe abort to orbit with a loss of one engine beginning at 40 seconds, and can fail-operational abort to orbit beginning at 190 seconds. Thus, a 166-second overlap exists between the two major abort modes. A return-to-launch-site analysis was also performed assuming that a 50 feet per second (fps) headwind existed (50 fps wind blowing in the direction of the launch azimuth). This wind profile only reduced the overlap by 1 second because most of the abort flight profile occurs at low dynamic pressures. Note that the single-stage-to-orbit all-rocket vehicle does not require any downrange abort sites to support this abort capability. Multiple engine-out aborts were also analyzed. This analysis was performed for the lox/LH<sub>2</sub> vehicle, but results should be similar for the tripropellant options (with the same number of engines).

The entry trajectory of the single-stage-to-orbit all-rocket vehicle is designed to not exceed the temperature capability of the thermal protection system, to not exceed a total acceleration of 1.5 G's, and to provide a cross-range capability in excess of 1,100 nautical miles. The entry thermal environment of the single-stage-to-orbit all rocket is less severe than that of the Space Shuttle. The strategy is to design deorbit targets that will result in the vehicle having a desired energy state and attitude at entry interface to allow heat rate and cross-range control during atmospheric entry. Modulation of the vehicle's bank angle and angle of attack during entry will provide control of both heat rate and cross-range capability. A sufficient control margin exists to allow the center of gravity of the payload to be anywhere along the longitudinal axis of the payload bay on the single-stage-to-orbit all-rocket vehicle.

#### Single-Stage-to-Orbit Feasibility

Single-stage-to-orbit rockets have long been known to be highly desirable, but their feasibility has always been questioned on margin and mass-fraction grounds. An analysis was performed to illustrate the effects of advancing technology on the assessment of the single-stage-to-orbit all rocket feasibility.

The propellant mass fraction, both required and achievable, is shown in figure 31 for three time frames. It is seen that whereas practical-sized vehicles were not attainable until a few years ago, technology that could be matured in the next several years would reverse that conclusion, yielding a larger mass fraction than required.

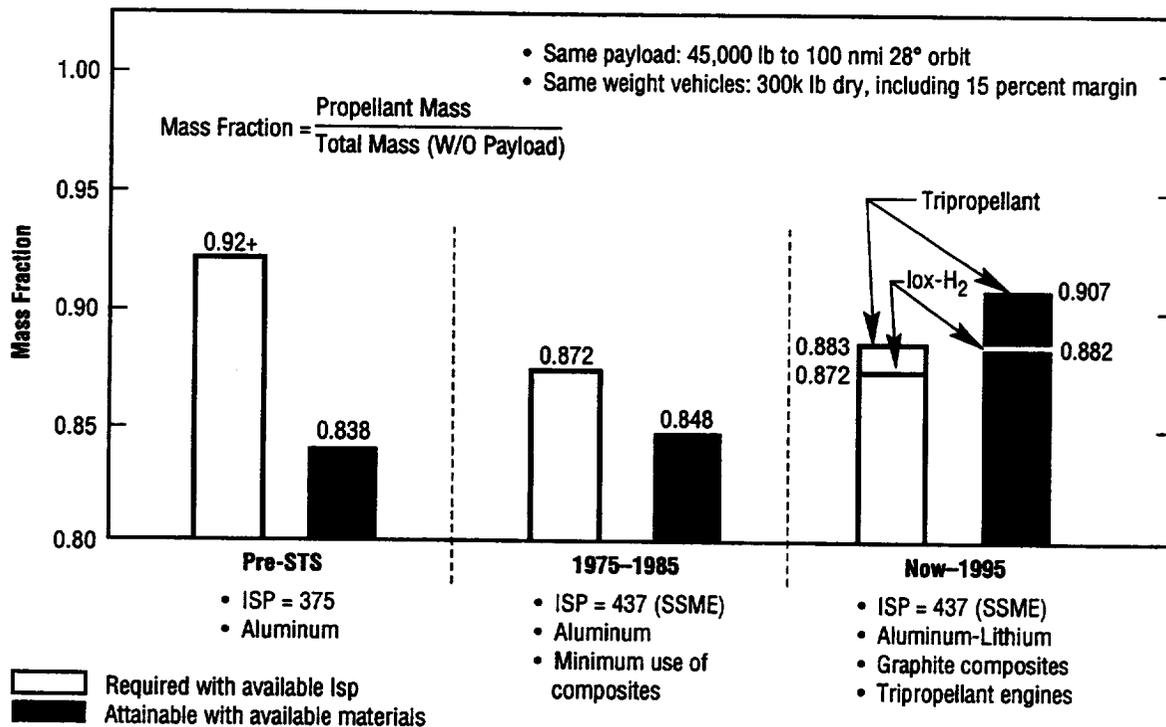


FIGURE 31.—Single-stage-to-orbit rocket vehicle mass fraction (for practical-sized vehicles).

This excess available mass fraction manifests itself in dry weight growth margin, with the bars of figure 32 indicating that the adoption of increasingly advanced technologies, proceeding cumulatively from left to right, shows rapidly increasing growth margin in the vehicle. Thus a single-stage-to-orbit vehicle that was infeasible using Space Transportation System (STS)-level technologies would allow dry weight to grow up to 31 percent without impacting the payload at all if the advanced technologies identified in this section are implemented. The existence of such a large margin indicates that development of single-stage-to-orbit vehicles can be considered with confidence once these technologies are matured and demonstrated.

It should be emphasized at this point that the reference single-stage-to-orbit all-rocket vehicle is not a maximum technology design. It uses Al-Li cryo tanks, composite structures, and tripropellant propulsion. The substitution of graphite-composite materials in the fuel tanks shows a large benefit and thus should be considered for this vehicle. In addition, there exist many advanced technologies that could offer the potential for an improved design, either in terms of performance or reliability, maintainability, and operability. These include new lightweight propulsion systems, multiposition nozzles, hot structures, conformal cryogenic tanks, low-pressure or pressure-stabilized cryogenic tanks, and use of slush hydrogen propellant. However, none of these latter technologies are considered sufficiently mature to include in a vehicle or in a near-term technology plan at this time.

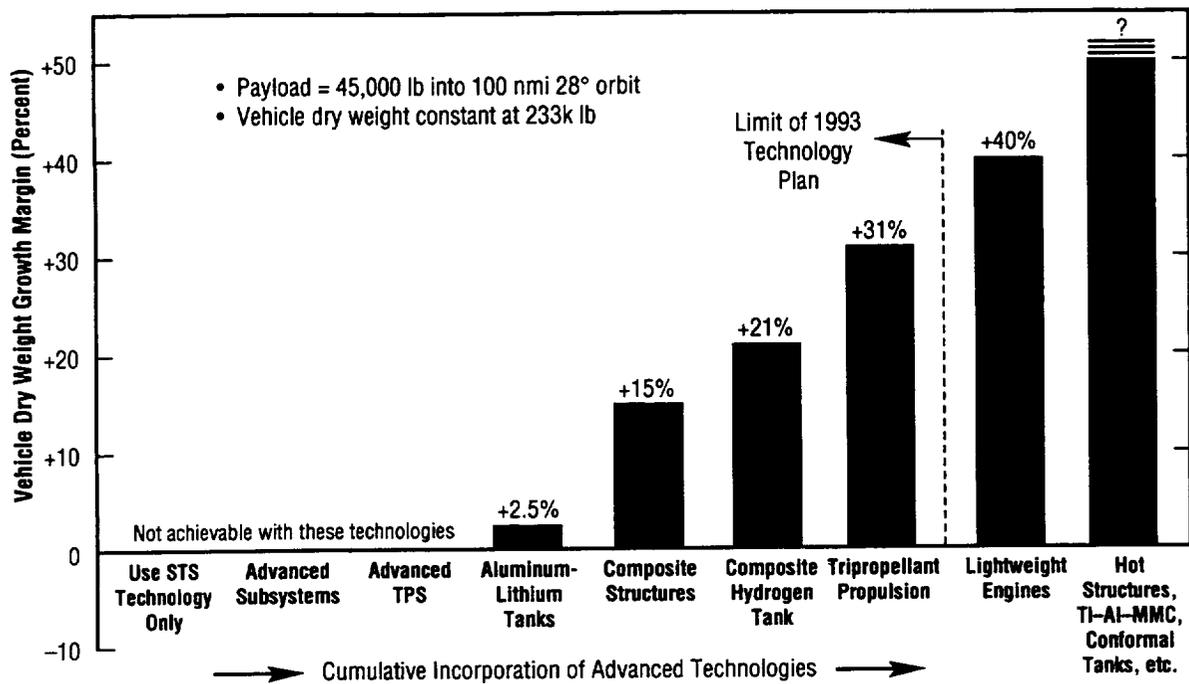


FIGURE 32.—Weight growth margin available.

### Operations Plan

Three fundamental approaches are evident in every modern aerospace endeavor, and all are equally important for a truly efficient launch capability:

- Design-in modern technology that can deliver a simpler vehicle
  - Design-out complex, less operable elements and subsystems (stages, hypergolics, ground support equipment, etc.)
  - Design-in operability (subsystem access, vehicle health monitoring (VHM), etc.).
- Eliminate flight-by-flight vehicle detailed inspection (almost a certification)
  - Proper margins proven in prototype testing
  - Confidence in subsystem status via vehicle health monitoring
  - Perform major overhauls and inspections in regularly scheduled depot maintenance periods (maintenance only by exception between flights).
- Manage for operations
  - Empower individuals to conduct full flight operations (program manager, crew chief, and flight manager)
  - Separate development from operations (3:1 staffing ratio, reduced sustaining engineering).

These philosophies and technologies will lead to a launch capability with fewer facilities, far fewer people, fewer unique tools, and much lower costs. A program that capitalizes on these benchmarks can dramatically reduce the infrastructure and, therefore, the costs associated with space launch. Under these philosophies, analyses of ground processing and flight operations have shown a reduction in the complexity of operations, facilities, and staffing required to conduct space launches. Operability is designed in from the start of the program.

## **Ground Operations**

Analysis indicates that using these operations philosophies, the single-stage-to-orbit all-rocket vehicle can deliver space launch capabilities with dramatically reduced operations costs. The single-stage-to-orbit all-rocket vehicle has eliminated Space Shuttle vehicle elements and associated Kennedy Space Center facilities and specialized support equipment. Well-established flight margins and a comprehensive vehicle health monitoring system will provide reduced pre- and post-flight testing requirements. These changes will reduce the dedicated Kennedy Space Center workforce requirements by 1,100 people. Coupled with a reduction in personnel support overhead (nontouch-to-touch labor ratio), reductions in Kennedy Space Center ground processing costs of up to 55 percent can be realized. Launch complex 39A or B will be modified to allow for single-stage-to-orbit launch. The vehicle will be processed in a hangar in the horizontal position, moved to the launch pad via a transporter, and erected to the vertical orientation.

Additionally, significant cost savings at non-KSC facilities are realized by the elimination of Space Shuttle elements: continuing production and shipment of the external tank, production and refurbishment of solid rocket motors, Spacelab, pre-planned product improvement, and other orbiter items (i.e., remote manipulator system). Elimination of these elements will reduce the dedicated workforce requirements by an additional 8,800 people.

## **Mission Design and Operations**

Similar to ground operations, the costs of mission design and operations can shrink substantially by the incorporation of modern operations technology and philosophies.

The concept of a crew chief will be applied to the mission design and flight operations activities. A team of engineers led by a mission manager will be assigned to each vehicle and given the responsibility for the mission design, definition of mission-unique software parameters, and real-time mission support. Each team will consist of 20–25 engineers with a support team to maintain the operations support center, software verification laboratory, and the required analysis tools and data bases. When necessary, additional systems support will be provided by the vehicle crew chief and ground team or depot maintenance team.

Given the autonomous operations for such areas as vehicle health monitoring, navigation, and targeting, and the use of automatic flight control systems built into the vehicle, the mission design and flight operations functions can be handled with a significantly reduced number of people from the number required by current Shuttle or expendable launch vehicle operations.

## **Summary of Development Strategy**

Based on focused government and industry surveys, the team has identified a set of desirable program attributes in the areas of management, technology maturation and development, production, operations, and maintenance. These include:

- Goals/objectives established at program start
- Quality and safety as top project priorities
- Strong customer involvement
- Streamlined budgeting/tailored acquisition procedures
- Single program manager with a small, centralized staff
- Small teams of expert staff
- Abbreviated reporting, coordinating, and review
- Limited interface specifications
- Utilize best commercial practices and standards
- Dedicated collocated design and development personnel
- Concurrent engineering
- Prototype approach to vehicle development.



The production phase will overlap the full-scale development and operations phases. At the end of the development phase, the new vehicle will be turned over to an operating organization. The CY2007 to 2009 time frame will serve to transition operations from the Space Shuttle fleet to the new vehicle fleet. No preplanned product improvements will be pursued. The only changes allowed on the new vehicle will be those required due to a defect or those that can be shown to pay for themselves in a reasonable period.

## **Technology Plan**

An Agency-wide subteam was established to assess current subsystem technology maturity levels for the three representative vehicle design options. The principal product of this subteam was the documentation of a plan to mature these technologies to a readiness level value of 6 by CY2000. Technology readiness level 6 is defined as "successful system/subsystem model or prototype demonstration in a relevant environment (ground or space)." The subteam has several working groups that consist of structures and materials, thermal protection system, propulsion, aerosciences, avionics, and operational specialists. The total technology plan was estimated to require \$900M over 5 years.

The result is a prioritized plan that identifies both enabling (requisite) and enhancing (upgrading) technologies. A core set of enabling technologies common to all three advanced technology concepts was also identified. These are discussed below.

### **Reusable Cryogenic Tanks**

A common element of fully reusable vehicles that has not been explored in any depth in prior technology efforts is the development of long life/low maintenance/operable reusable cryogenic tank systems. The cryogenic tank system includes both the tank structure and insulation (both cryogenic and aerothermal). Included in this task are the development of tank certification criteria; nondestructive evaluation (NDE) techniques; establishment of a materials data base; optimization of materials processing and fabrication; the design, fabrication, and analysis of a large-scale cryogenic tank system including structural and thermal cycling; and incorporation of vehicle health monitoring.

### **Vehicle Health Management and Monitoring**

Vehicle health management and monitoring, while being successfully and widely utilized on high-performance military and commercial aircraft, is not nearly as mature on domestic space launch systems, with the exception of certain subsystems on the Space Shuttle. Application of these existing techniques to launch vehicles permits real-time identification and rectification of vehicle subsystem anomalies. Definition of critical items to be monitored and stored, development of data transfer techniques, "smart" management algorithms, and development of ground processing procedures, including responsive maintenance capabilities, are included in this area.

### **Autonomous Flight Control**

To achieve low cost space transportation, most in-flight functions must be automated and control responsibility transferred to the vehicle. Autonomous flight control is both possible and near state of the art for ascent, re-entry and landing. On-orbit operations, such as routine rendezvous and docking at the Space Station, are also near state of the art and are under development by NASA. The technology objective is to develop and demonstrate these integrated techniques.

### **Operations Enhancement Technologies**

The focus on low operations cost approaches for launch systems has resulted in an assessment of operations requirements derived from a series of studies and benchmark evaluations. Several key areas requiring further investigation include: operable and reliable rocket engines, leak-free propellant feed valves and joints, electro-mechanical actuators, and electrohydraulic actuators.

### **Long Life/Low Maintenance Thermal Protection System**

The development of a long-life/low-maintenance thermal protection system is required to decrease the operational costs of reusable vehicles. Tasks to investigate metallic concepts, toughened rigid ceramic insulation, advanced flexible blanket insulation, carbon/silicon-carbide hot structures, and direct-bond reusable surface insulation are included in this area.

### **High Priority Vehicle-Unique Technology/Advanced Development**

For the single-stage-to-orbit all-rocket concept, the key technology requirement is for the development of a long life, low maintenance, tripropellant engine generally based on the Russian RD-704 design. An alternate approach would be the development of appropriate technologies for an advanced lox/LH<sub>2</sub> engine derived from the Space Shuttle main engine.

## **Costs**

This section includes Option 3 cost estimates over the life of the program. All transportation costs to launch NASA and Department of Defense payloads from 1994 to 2030 are included. The life-cycle costs include: the cost of operating current systems (Space Transportation System, Titan IV, Atlas, Delta) from 1994 until replacement; technology, design, development, test, and evaluation; facilities; vehicle fleet production (including production of vehicles for anticipated reliability losses); and recurring operations. In addition to the vehicle costs, the design, development, test, and evaluation, and production costs for a crew rotation module and an upper stage are included.

Design, development, test, evaluation, and production estimates are business-as-usual estimates and take no credit for potential cost savings that can be achieved by using new ways of doing business or more efficient management or procurement approaches (e.g., “Skunk Works”). A savings of 30–40 percent over these numbers could be expected if such new ways were adopted. Operations cost estimates do require a significant departure from the current Space Transportation System operations culture and reflect the ground rules and philosophy detailed earlier.

Table 7 shows the total cost from 1994 to 2030 of each cost element for the two options of the single-stage-to-orbit all-rocket vehicle using the RD-704 engine. Note that the 45-foot payload bay vehicle has significantly lower expendable launch vehicle costs since it was assumed to replace the Titan IV as well as all other current vehicles.

Figure 34 shows the cost profile from 1994 to 2030 for the architecture featuring the single-stage-to-orbit all-rocket vehicle using the RD-704 engines with a 45-foot payload bay.

## **Option 3 Team Findings**

### **Comparison Against Criteria**

The single-stage-to-orbit all-rocket vehicle meets the fundamental requirement established at the outset of the study to satisfy the national launch needs. The focus of the study was in defining a 25k-pound class of launcher since approximately 90 percent of all future payloads fall into this category. The advanced technology vehicle will replace all Delta- and Atlas-class missions and meet Space Station logistics resupply and return requirements (cargo and crewed). The vehicle is capable of performing on-orbit payload servicing missions when required. The tripropellant aspect also allows for an option to carry a 45-foot long payload bay to accommodate Titan IV-class payloads.

The single-stage-to-orbit all-rocket vehicle also has the potential for increasing crew safety and vehicle reliability. The vehicle is capable of performing a return-to-launch-site maneuver with one engine failure on the launch pad. Abort with multi-engine failures is possible during the ascent phase. In the crewed configuration, the crew pressure vessel is designed to survive a catastrophic failure, with ejection seats for escape. Avionics fault tolerance is fail op/fail safe. Engine shutdown is possible due to all liquid propulsion. Reliability is also enhanced through the use of a single airframe, which inherently reduces the number of vehicle systems.

TABLE 7.—Single-stage-to-orbit all rocket vehicle costs

Total Costs (\$B) FY94–FY2030*		
SSTO(R) (RD-704)		
	30-ft Payload Bay	45-ft Payload Bay
<b>Technology Development</b>	<b>0.9</b>	<b>0.9</b>
<b>DDT&amp;E</b>	<b>16.7</b>	<b>17.1</b>
• Vehicle	13.9	14.3
• Crew Rotation Module	2.2	2.2
• Upper Stage	0.6	0.6
<b>Facilities</b>	<b>0.6</b>	<b>0.6</b>
<b>Production</b>	<b>18.1</b>	<b>18.7</b>
• Vehicle	12.6	13.2
• Crew Rotation Module	0.8	0.8
• Engine	4.7	4.7
<b>Operations</b>	<b>161.7</b>	<b>131.9</b>
• Vehicle	23.9	23.9
• STS	49.1	49.1
• ELV	85.8	56.0
• Upper Stage	2.9	2.9
<b>Total</b>	<b>198.0</b>	<b>169.2</b>

\* Dollar amounts given in FY94 values.

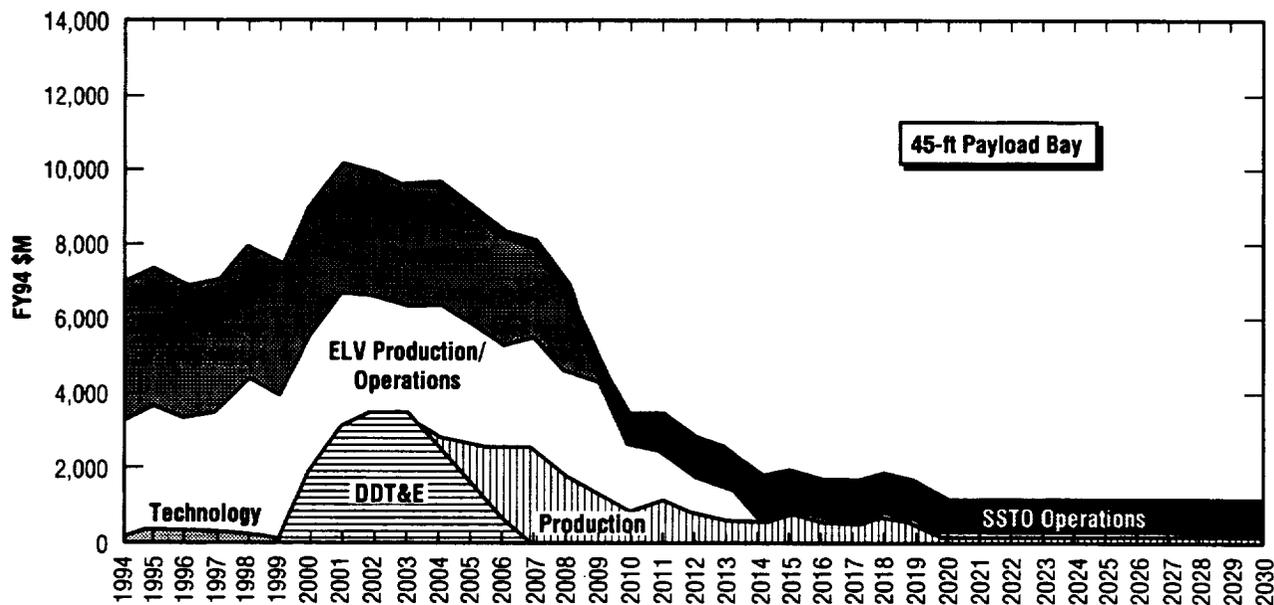


FIGURE 34.—Access to Space Option 3 single-stage-to-orbit all rocket total cost spread.

The focus of the Option 3 effort was on reducing annual operations costs. The single-stage-to-orbit all rocket annual operating costs are estimated to be approximately one-third that of the Space Shuttle. This is possible through the use of a single, fully reusable airframe coupled with changes in the space launch operations culture. Development costs of approximately \$18B were estimated using a NASA business-as-usual approach and appear reasonable for this type of system. A 30–40 percent reduction could be expected with new ways of doing business. Even without flying the Titan IV payload missions, payback on the initial investment will occur approximately 9 years from initial operating capability. Risk is mitigated through the use of evolutionary technologies based on proven systems and a technology maturation program prior to initiation of full scale development, coupled with a prototype test vehicle to reduce both technical and programmatic risk. If the technologies do not mature prior to full-scale development, the option exists for terminating future development and applying the technologies to the existing expendable and Shuttle launch vehicle fleets.

A high flight rate coupled with full reusability will yield cost-effective and competitive space access for commercial payloads. The Option 3 recommended program is focused on technology development and application that will result in a significant technology data base for use by the private sector. Potential dual-use technologies include applications to existing and future launch systems and high-strength/lightweight composite structures.

### **Summary**

The Option 3 team has defined a strategy to meet reduced cost future space transportation needs, with a primary focus on improving reliability, crew safety, and operability. An approach has been defined that will offer significant reductions in annual operations costs. The advanced technology approach, Option 3, meets these needs by defining a transportation architecture that contains an all rocket single-stage-to-orbit launch vehicle to accommodate both Space Station resupply and 25,000 to 41,000 pound cargo delivery and satellite deployment missions (NASA, DOD, and commercial) in CY2008, as well as an interim expendable launch vehicle program that upgrades the existing Delta, Atlas, and Titan fleet in the CY2000 to 2008 time frame. The final architecture of Option 3 is shown in figure 35.

Based on preliminary evaluations, single-stage-to-orbit vehicles appear to be feasible because of reduced sensitivity to engine performance and weight growth resulting from use of near term advanced technologies (e.g., tripropellant main propulsion, Al-Li and graphite composite cryogenic tanks, graphite-composite primary structure, etc.). An incremental approach has been laid out to reduce both technical and programmatic risk. This includes maturing the required technologies to a technology readiness level of 6 prior to full-scale development (i.e., ground tests and experimental vehicles) and conducting a prototype flight test program that will define the operational envelope of the vehicle and thus certify the design for production and operations.

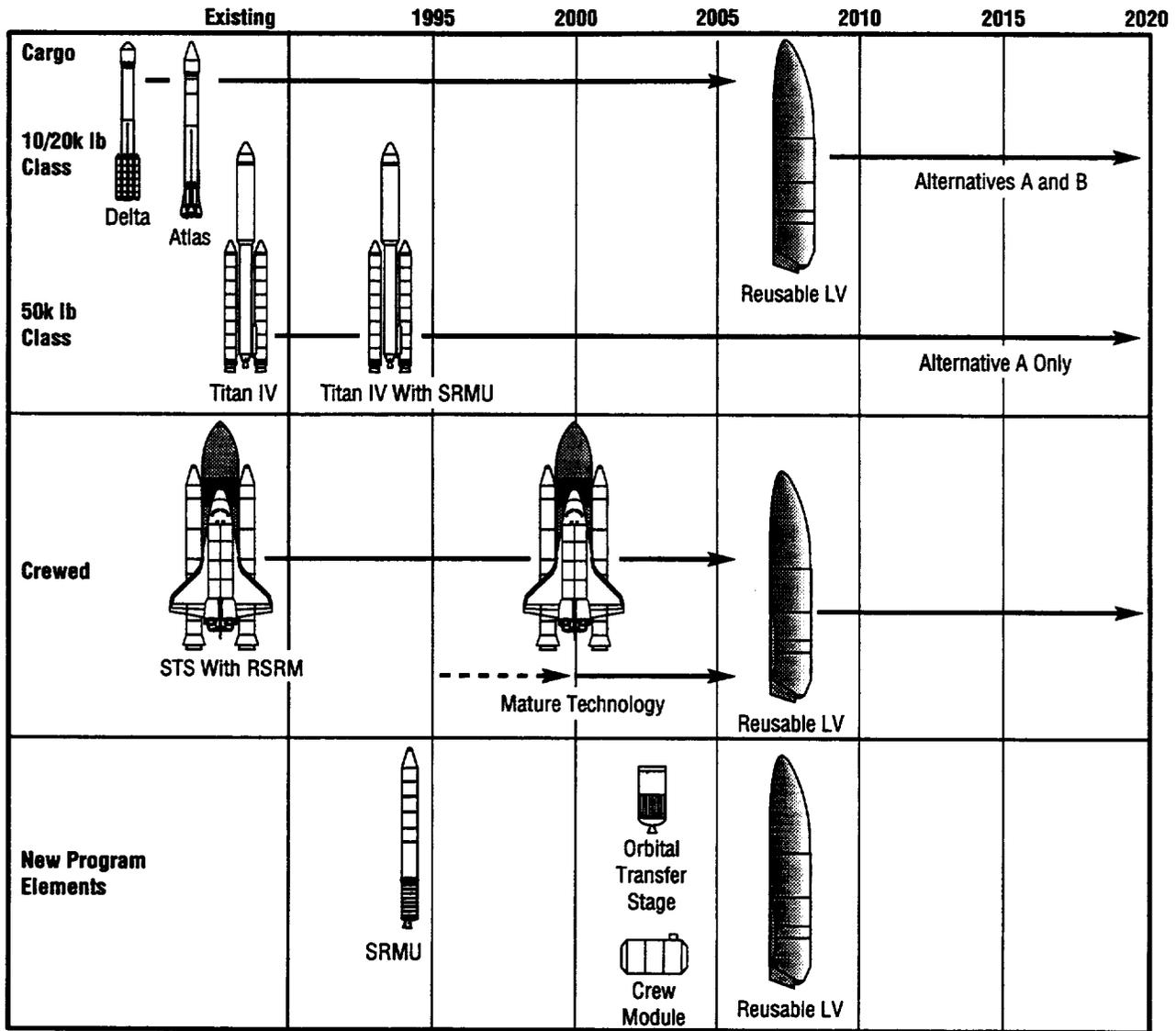


FIGURE 35.—Advanced technology architecture.

The goal to lower the cost of routine access to space has been demonstrated in this option with a fully reusable launch vehicle that captures Delta, Atlas, Titan, and Shuttle missions at approximately 20 percent of the current combined annual operating costs of these systems.

Affordable, routine access to space will only be achieved when today's space flight infrastructure is decreased substantially. This is particularly true in the area of operations where vehicle processing, mission planning, and flight execution must be significantly streamlined. Improvements can and should be made in the existing Delta, Atlas, Titan, and Shuttle systems with infusion of advanced technologies and streamlined management techniques. However, the basic high-cost infrastructure will remain due to the design characteristics of the vehicles—multiple stages, solid stacking, ocean recovery and reconditioning, performance limitations, and so forth. The single-stage-to-orbit all-rocket vehicle is capable of delivering these necessary infrastructure reductions through the use of technology enhancements that offer increased margins simultaneously with major increases in operability. Additionally, a large portion of the reduction can be attributed to the elimination of major systems such as the external tank, solid rocket boosters, multiple stages, and so forth.

*The bottom line is this: operability must not be simply a goal; it must be THE design driver.*

# Option Team Down-Selects

The most beneficial architectures as recommended by the Option teams are shown in the shaded areas in figure 36. These architectures were presented to the study steering group. They were then subjected to comparative analysis from which a preferred architecture was to be selected.

Option 1	Option 2	Option 3
Shuttle-Based	Conventional Technology	New Technology
<ul style="list-style-type: none"> <li>• <b>Retrofit: Evolutionary improvements. Keep the current ELV fleet.</b></li> <li>• New Build: Above changes plus major internal mods; new orbiter. Keep the current ELV fleet.</li> <li>• New Mold Line: Above changes plus major external mods; new orbiters and boosters. Keep the current ELV fleet.</li> </ul>	<ul style="list-style-type: none"> <li>• 84 configurations with differing crew carriers, cargo vehicles, stage configurations, engine types, and number of new vehicles. Reduced to four primary candidate architectures:               <ul style="list-style-type: none"> <li>- (2A): New large vehicle                   <ul style="list-style-type: none"> <li>• Keep Atlas, Delta ELV's</li> <li>• HL-42 plus ATV</li> </ul> </li> <li>- (2B): New lg. and sm. vehicle                   <ul style="list-style-type: none"> <li>• Keep Delta ELV</li> <li>• CLV-P for crew plus cargo</li> </ul> </li> <li>- (2C): New lg. and sm. vehicle                   <ul style="list-style-type: none"> <li>• Keep Delta ELV</li> <li>• HL-42 plus ATV</li> <li>• Hybrids; STME engines</li> </ul> </li> <li>- (2D): <b>New lg. and sm. vehicle</b> <ul style="list-style-type: none"> <li>• <b>Keep Delta ELV</b></li> <li>• <b>HL-42 plus ATV</b></li> <li>• <b>RD180/J2S engines</b></li> </ul> </li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>• <b>3A: Single-stage-to-orbit all rocket</b> <ul style="list-style-type: none"> <li>- <b>With Titans</b></li> </ul> </li> <li>• <b>3B: Single-stage-to-orbit all rocket</b> <ul style="list-style-type: none"> <li>- <b>No ELV's</b></li> </ul> </li> <li>• Single-stage-to-orbit air-breather/rocket               <ul style="list-style-type: none"> <li>- No ELV's</li> </ul> </li> <li>• Two-stage-to-orbit air-breather/rocket               <ul style="list-style-type: none"> <li>- No ELV's</li> </ul> </li> </ul>

FIGURE 36.—Architectural alternatives proposed by the teams.

The Option 1 team down-selected to the Retrofit Alternative. This is the alternative that incorporated only internal changes to the Space Shuttle orbiter, retrofitted them into the fleet as the orbiters came in for major maintenance, and replaced orbiters only for attrition. The rationale for the down-select was that this alternative had the lowest design, development, test, and evaluation cost, while enabling about the same level of annual operations cost savings as the other alternatives.

The Option 2 team down-selected to the 2D architecture. This is an architecture that built a new expendable 20k-pound payload launch vehicle to replace the Atlas, a new 85k-pound lift expendable vehicle to replace the Titan and the Shuttle, separate new cargo and crew carriers, and the single-engine Centaur upper stage. It kept the Delta as a cost-effective launcher for smaller payloads. The principal reasons for the down-select were that this alternative did not require new engine development (the RD180 was claimed to be a low-risk modification of the currently operational RD170), had low life-cycle costs, and had the lowest operations costs for the Atlas-class missions, which have a high level of commercial interest. It accepted the limitations inherent in reduced down-mass capability from the Space Station.

The Option 3 team down-selected to an all-rocket, fully reusable single-stage-to-orbit vehicle. The recommended configuration for this vehicle incorporated a tripropellant propulsion system, graphite-composite structure, aluminum-lithium propellant tanks, and an advanced thermal protection system and subsystems. Added margin could be attained by using graphite-composite fuel tanks rather than those made with aluminum-lithium fuel tanks. Rocket vehicles were selected over air-breathing vehicles on the basis that they had lower design, development, test, and evaluation costs; lower technology phase costs; and required less demanding technology that would translate into a more quickly developed and less risky program.

Two versions of the single-stage-to-orbit rocket were recommended. The first (Option 3A) had a transverse payload bay 15 feet in diameter and 30-feet long, which could not accommodate the largest of the Titan-class missions. This architecture thus required continuation of the Titan expendable launch vehicles in parallel with the new vehicle operations. The second version of the single-stage-to-orbit rocket vehicle (Option 3B) had a 45-foot long longitudinal payload bay that could accommodate all Titan payloads if some were somewhat downsized (a plan which is under serious consideration within the Department of Defense), and thus would not require continuation of expendable launch vehicles as part of the architecture. This version was included because of the high costs of operating the Titan expendable launch vehicle.

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# New Operations Concept

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All the option teams recognized that if large savings in annual costs were to be realized, new management, contracting, design, development, and, particularly, operations concepts had to be devised. The fundamental change required was that all phases had to be driven by efficient operations rather than by attainment of maximum performance levels. This, in turn, required maximizing automation and minimizing the number of people in the "standing army" on the ground, as well as requiring redundancy, engine-out capability, and robust margins in all subsystems. In addition, both of the Options 2 and 3 teams recommended avoiding development of new technology in parallel with vehicle development in order to minimize program risks and cost growth.

The Options 2 and 3 teams recommended a streamlined management and contracting approach patterned after the Lockheed "Skunk Works," which features smaller, but dedicated and collocated government oversight, a more efficient contractor internal organization, rapid prototyping, and team continuity from design to flight.

The recommendations also included a number of specific operations-oriented items, some of which are applicable to reusable vehicles and others that apply to both expendable and reusable vehicle operations. They included using well-matured technologies, demonstrated through a number of flights of an experimental vehicle; demonstration and validation of vehicle design via flights of a full-scale prototype, with gradual stretching of the flight envelope; certification of the vehicle design and type-certification of the fleet; avoiding continual engineering changes and long-term development engineering overhead by freezing the design for long periods between block changes; avoiding most detailed inspection and maintenance after each flight unless the need is clearly indicated by an onboard health monitoring and reporting system, or if the immediately previous flight exceeded the flight envelope limits charted in the prototype program; operating the single-stage-to-orbit fleet using a depot maintenance philosophy in which maintenance is only done by exception or every 1 to 2 years; use of small, dedicated ground crews led by a crew chief empowered to make all decisions in operations and maintenance; a reduced ratio of nontouch to touch labor compared to that utilized in today's operations; and much use of automation on the ground, as well as in the vehicle. These amount to a complete change in the way vehicles are developed and operated compared to current practice, and are patterned after several high-performance aircraft programs.

In the aggregate, the above recommendations amount to a "new way of doing business," which was recognized as being essential if low operating costs were to be realized. Its attainment would be a major shift from today's practices in launch vehicle operations.

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# Comparative Analysis

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The down-selected architectures were compared so that a decision could be made on the most attractive option. The major factors considered in the evaluation were design, development, test, and evaluation costs; operations costs; life-cycle costs; and the safety and reliability of the concepts. These and other factors considered followed the major evaluation criteria identified in the Purpose section.

## Costs Assessment

The costs presented in this report were developed from a common set of ground rules developed by the Comptroller's Office and are predicated on the technical complexity, operability, and flight-related assumptions of each of the option teams. The costs of the recommended architectures were analyzed, with design, development, test, and evaluation and total program costs treated separately. All cost figures are shown in constant FY94 dollars and in a business-as-usual mode, that is, without incorporation of the operations or management changes discussed in the New Operations Concepts section. This is because the NASA cost models were designed around the historical data base, and NASA does not have a mature basis for estimating costs incurred in a different culture.

The NASA Comptroller assembled a cost team to attempt to estimate the savings that might accrue if new ways of doing business were adopted, and this team concluded that a 30 to 40 percent reduction of the costs shown might be expected operating in such a mode. However, the cost team felt that since each of the options benefited differently from changes in culture, the comparison of the different options would be best served by using the business-as-usual method and then applying estimated reduction factors.

The design, development, test, and evaluation costs of the three options are shown in figure 37. These curves include a technology phase for Option 3. The curves are annotated with a callout indicating the total technology, design, development, test, and evaluation costs, which are \$2.4B for Option 1; \$11.1B for Option 2; and \$17.6 and \$18B for Options 3A and 3B, respectively. These curves do not include facilities, production, or operations. If the new ways of doing business were adopted, these costs could be as much as 30 to 40 percent lower, or \$1.5 to \$1.7B for Option 1; \$6.7 to \$7.7B for Option 2; and \$10.6 to \$12.6B for Option 3.

The profiles of these technology, design, development, test, and evaluation expenditures are very different. Options 1 and 2 require large budgets essentially immediately, while Option 3 has a 4 to 5 year technology phase funded at relatively modest levels before the large budget requirements start. This technology phase requires \$900M over 5 years and has an annual peak of about \$240M. The profiles of Options 3A and 3B are essentially the same.

The life cycle cost profiles of the three options are shown through the year 2030 in figure 38. These are total costs for the entire period to deliver the mission model of the Approach, Ground Rules, and Organization section, and include the technology, design, development, test, and evaluation costs of figure 37. A fourth curve is included in figure 38, labeled "current systems," which represents the cost to the U.S. Government if no changes are made and the current systems are operated for the entire period. In 1995, this current systems cost will be comprised of \$3.8B for the Space Shuttle, \$2.4B for the Department of Defense expendable launch vehicles and infrastructure, and \$0.5B for the NASA expendable launch vehicles, totaling \$6.7B.

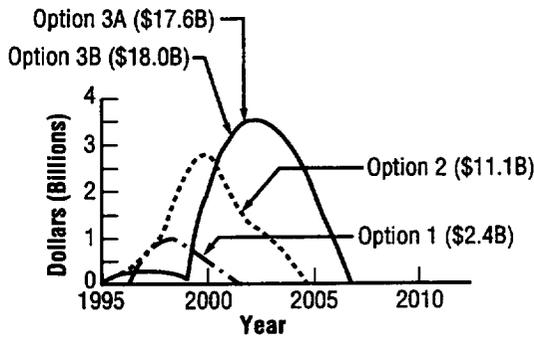


FIGURE 37.— Design, development, test, and evaluation costs of the options.

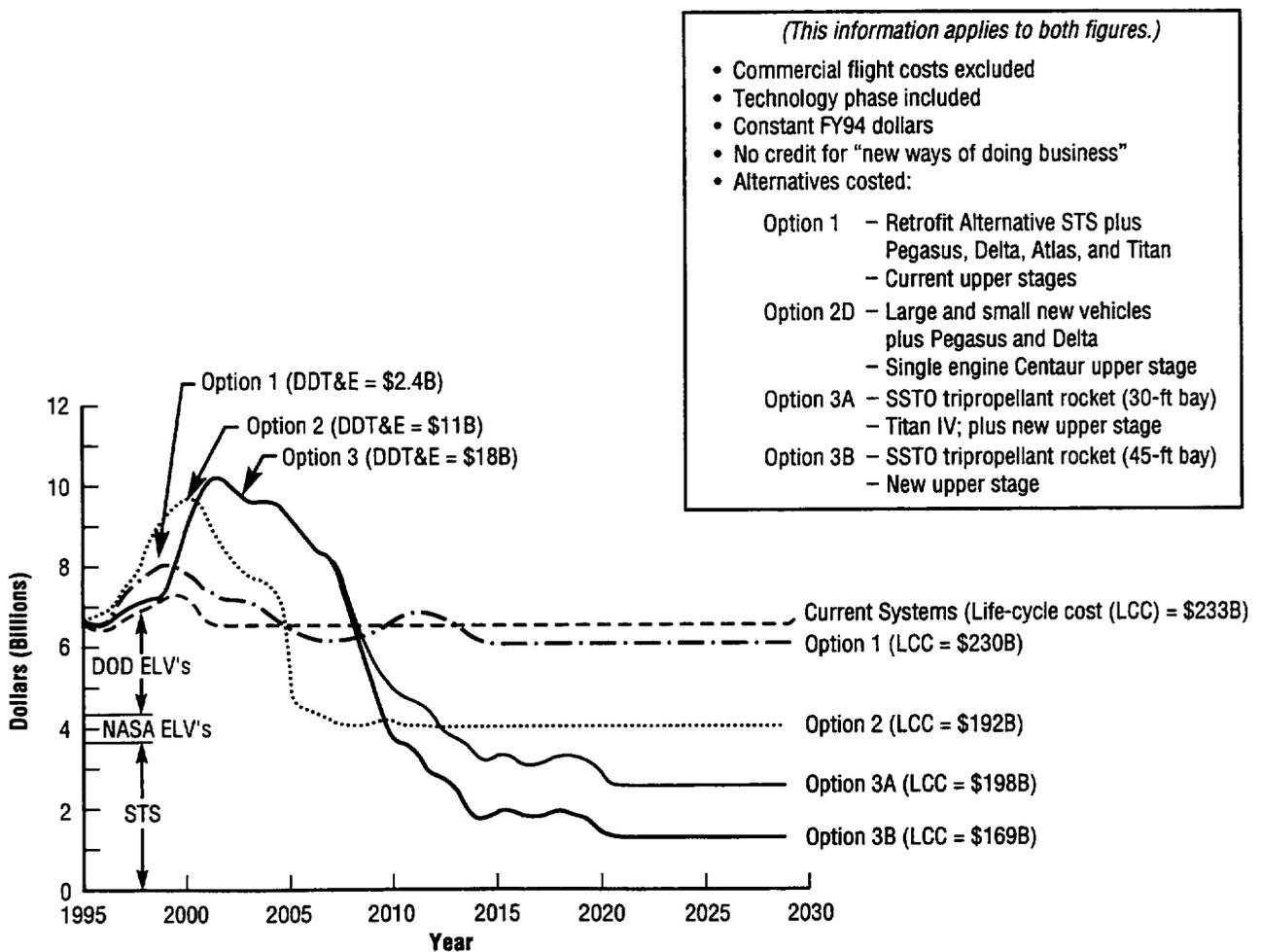


FIGURE 38.—Total U.S. Government launch costs.

This reference varies somewhat with the expendable launch vehicle annual buys, infrastructure investments, and programmed Shuttle improvements. It was assumed as a point of reference that the expenditures remain essentially fixed after 2000, and that no additional orbiters will be acquired through 2030, even though a replacement orbiter is likely to be needed sometime during that interval. The life-cycle cost of this activity, if nothing is done differently than today, is \$233B through 2030.

The cost plot of the architecture of Option 1 shows the increase for the \$2.4B investment, followed by the \$6.5B to retrofit the fleet, and then by a programmed buy of a replacement orbiter in 2010. The annual realized savings in operations costs is only about \$0.25B per year. Its life-cycle costs are \$230B. The investment in design, development, test, and evaluation is recovered after 10 years of steady-state operations. The total investment including design, development, test, and evaluation, and the replacement orbiter is recovered in slightly more than 20 years of operation.

The cost plot of the architecture of Option 2 shows the investment of \$11.1B in design, development, test, and evaluation costs upon the immediate start of new vehicle development, followed by a rapid reduction in the operations costs starting in 2005 when the new vehicles are introduced and the Shuttle and most expendable launch vehicles are phased out. These vehicles are all phased out over 2 years. The operating costs are reduced to \$4B annually beginning in 2006. The life-cycle costs of Option 2 were \$192B. The recovery time for the investment in design, development, test, and evaluation is about 4 years of steady-state operation. The recovery of the total design, development, test, and evaluation plus production investment is about 5 years of steady-state operation.

The plot of the architecture of Option 3A shows the investment of \$17.6B for technology, design, development, test, and evaluation through 2008, with the start of the development program delayed by about 5 years due to the technology maturation and demonstration phase. This option features the vehicle with the shorter payload bay, which requires continuation of the Titan expendable launch vehicles in parallel.

The Option 3A architecture results in a steady-state operations cost of \$2.6B per year. That level is not achieved until after 2020 due to a deliberately slow production phase for the reusable vehicles and upper stages and their spares, which are all purchased continuously and then the production line is shut down. These purchases are stretched over 10 years or more to minimize peak funding needs. The technology, design, development, test, and evaluation investment would be recovered in 4 ½ years of steady-state operations, while recovery of the total investment, including production of the vehicles, requires 9 years. The life-cycle cost of Option 3A is \$198B.

Option 3B has the longer payload bay and could carry all DOD payloads with some downsizing, which the DOD may accomplish at the program's block change time in the first part of the 2000 to 2010 time period. The cost profile for this option follows that of Option 3A during development, but decreases to an annual operations cost of \$1.4B since no Titans need to be retained. The life-cycle cost for this option is \$169B. The technology, design, development, test, and evaluation investment would be recovered in only 3 ½ years of steady-state operation, while recovery of the total investment would take only 7 years.

The clear message from figure 38 is that new vehicles are required if substantial savings are desired, and that attaining the greatest savings requires the largest investment.

The most significant aspects of the costs of the three options, and some associated metrics, are shown in figure 39. This figure displays the costs for the technology phase, the design, development, test, and evaluation (including the technology phase), the production of one-time or reusable hardware, the annual operations costs in the out-years, and the life-cycle costs.

In addition to the previous observations, it is important to note that if nothing is done differently, the U.S. Government will spend \$233B for space launch through 2030 for the assumed mission model of section 2. Option 1 only reduces that total by \$3B over 35 years. Option 2 reduces the life-cycle cost by \$41B in non-discounted dollars, or 17.6 percent. Option 3A reduces the life-cycle cost by \$35B, or 15 percent. Option 3B reduces the life-cycle cost by \$64B, or 27.5 percent.

Thus, the life-cycle cost savings for Option 3B are the greatest of all of the options, averaging a savings of \$1.8B per year over the 35 year period through 2030.

		Current Program	Option 1 (Retrofit + ELV Fleet)	Option 2 (Lg. + Sm. Veh. + Delta)	Option 3	
					(SSTO-R, 30-ft Bay + Titan)	(SSTO-R, 45-ft Bay)
<b>Costs</b>	Technology	0	Incl. in DDT&E	\$0.4B	\$0.9B	\$0.9B
	DDT&E (Incl. Technology)	0	\$2.4B	\$11.1B	\$17.6B	\$18B
	Production	0	\$5.6B	\$2.0B	\$18.1B	\$18.7B
	Operations (Out-Years)	\$6.4B/yr	\$6.1B/yr	\$4.0B/yr	\$2.6B/yr	\$1.4B/yr
	Life-Cycle Costs	\$233B	\$230B	\$192B	\$198B	\$169B
<b>Operations Cost Metrics**</b>	Average \$/Launch (Shuttle Replacement)	\$322M (STS)*	\$293M (STS)*	\$85M (Sm.) \$205M (Lg.)	\$41M	\$38M
	\$/lb of Payload (Fleet Average for Mission Model)	\$7,488/lb	\$6,814/lb	\$6,100/lb	\$3,900/lb	\$2,100/lb
	\$/lb of Payload (Full Veh., to LEO, 28°)	\$6,850/lb (STS)*	\$6,234/lb (STS)*	\$3,900/lb (Sm.) \$1,600/lb (Lg.)	\$980/lb	\$920/lb
	\$/lb of Payload (to the Space Station)	\$12,880/lb	\$11,720/lb	\$3,700/lb (Lg.)	\$1,600/lb	\$1,500/lb

- \* Current Space Shuttle capability (no ASRM)
- \*\* In the out-years
- Constant FY94 dollars; no "new ways of doing business."

**FIGURE 39.—Summary of option costs.**

Referring to the cost metrics portion of the figure 39, it is shown that the fleet-average launch costs for the mission model were reduced from the current values of \$7,488 per pound to \$6,814 per pound for Option 1; \$6,100 per pound for Option 2; \$3,900 per pound for Option 3A, and to \$2,100 per pound for Option 3B. The lowest cost per pound of payload for the new vehicles launching into a 28-degree inclination low orbit were \$920 and \$980 per pound for the two Option 3 cases. Next higher were the \$1,600 per pound to \$3,900 per pound for the two different sized vehicles in Option 2, with the commercially significant smaller vehicle having the larger cost per pound. The cost for Option 1 was \$6,234 per pound.

The Space Shuttle costs per launch were calculated consistent with the methodology historically presented to OMB and GAO. While all the costs were lower than the \$6,850 to \$7,488 per pound for the current Shuttle program when computed the same way, it is clear that the major cost savings targeted as a goal for this study only accrue in architectures employing new vehicles. In addition, it is also clear that Option 3 lowers the launch costs by the largest amount.

The cost per launch to a Space Station in a 220 nautical mile circular, 51-degree orbit showed similar trends, the lowest being \$38 to \$41M for Options 3A and 3B, \$85 to \$205M for the Option 2 vehicles, and \$293M per launch for the Space Shuttle, computed in the same way. The cost per pound of payload to the new Space Station orbit also showed similar trends.

It is possible that the above operations cost metrics might be reduced further by adopting the so-called new ways of doing business, but the savings obtained may be less than the 30 to 40 percent predicted for the design, development, test, and evaluation, and production reduction. This is because the operations costs are already based on streamlined operations concepts, at least for Options 2 and 3. In addition, further reductions may be possible by buying launch services from the private sector, but the effects have not been well quantified.

It is clear from examination of the cost results that large annual cost savings are possible, but they can only be attained by considerable up-front investment—the larger the investment, the larger the operations cost savings. It is also clear that the attainment of costs substantially below about \$900 per pound of payload into a 28 degree low-Earth orbit requires further understanding of the savings obtainable with new ways of doing business, larger mission models requiring more frequent flights, technology beyond that of any alternatives considered in this study, or, most likely, a combination of all these factors.

## Other Assessment Factors

Eight major factors were assessed, including a summary of the costs from the previous figure. These assessment factors are displayed in the matrix of figure 40.

	Option 1 Shuttle Retrofit	Option 2 Architecture 2D (Lg. + Sm. + Delta)	Option 3	
			SSTO Rocket + Titan	SSTO Rocket
<b>National Launch Needs</b>	Meets Model	Meets Model Except 125k lb/yr Downmass (Provides 25k lb)	Meets Model	Meets Model (If DOD P/L Shortened)
<b>Vehicle Reliability</b>	Meets 0.98 Goal for Shuttle and Delta	Meets 0.98 Goal for New Vehicles and Delta	Meets 0.98 Goal for New Vehicle	Meets 0.98 Goal
<b>Crew Safety</b>	Does Not Recommend Significant Improvement	Meets 0.999 Goal	Meets 0.999 Goal	Meets 0.999 Goal
<b>Summary Costs</b>	Does Not Approach 50 Percent Reduction Goal	Approaches 50 Percent Reduction Goal	Exceeds 50 Percent Reduction Goal	Far Exceeds 50 Percent Reduction Goal
<b>Operability</b>	Significant Shuttle Improvement. ELV Fleet As Is	New Vehicles: Robust and Highly Operable. Delta, Pegasus As Is	New Vehicles: Robust and Highly Operable. Titan As Is	New Vehicles: Robust and Highly Operable.
<b>Technical Risk</b>	Low	New Vehicle—Low; HL-42—Moderate	Moderate-to-High	Moderate-to-High (More Technology Required)
<b>Cost Risk</b>	Low-to-Moderate	Moderate	Moderate-to-High	Moderate-to-High
<b>Other Factors</b>	Additional Orbital Capabilities	Achieves Parity With International Competitors	Major Increase in International Competitiveness	Major Increase in International Competitiveness

FIGURE 40.—Option comparison.

## National Launch Needs

All the options met the requirement to launch the mission model of the Purpose section. The requirement also existed to return all of the mass taken to the Space Station, which was met by Options 1 and 3, but not by Option 2, which returned only approximately 20 percent. This was a feature of the down-selected architecture, and was adopted in order to minimize new vehicle and carrier sizes and costs. The cost of the expended Space Station carriers and racks resulting from this limitation were accounted for in the operations cost analysis.

An additional factor applied to Option 3B, which was able to launch the longest DOD payloads only if the DOD downsized them to 45-feet in length. Preliminary discussions with the DOD indicated that such downsizing was a distinct possibility at the time the payloads were due for a block change, about 2002. Indeed, there has already been some Congressional language urging the DOD in this direction in order to allow retirement of the expensive Titan vehicles. Thus, while the possibility of having shorter payloads might be realistic, nonetheless, the viability of Option 3B rests on this assumption.

## **Vehicle Reliability**

All vehicles except the Atlas and Titan met the goal of having a vehicle reliability greater than 0.98 percent. It was felt that it was unlikely that these two expendable launch vehicles could be upgraded to that reliability in a cost-effective way, while the Delta is almost at this reliability level already. All the new vehicles were designed to exceed this requirement.

## **Crew Safety**

The improvement of crew safety (probability of crew survival) to at least 0.999 from the 0.98 of the Space Shuttle was met or exceeded by the new vehicles of Options 2 and 3. Option 2 had a launch escape propulsion system for the entire crew carrier, while Option 3 adopted escape seats and intact abort of the vehicle into orbit or return to the launch site.

Option 1 did not recommend the addition of escape seats, an escape pod, or liquid boosters to the Shuttle and, thus, did not improve significantly on the current crew safety analysis. The reason for this recommendation was that the analysis showed that the expense for incorporation of additional escape capabilities was high, and that there was a significant impact on current vehicle capabilities due to factors such as a major shift in the orbiter center of gravity.

## **Summary Costs**

The costs discussed with reference to figure 39 indicate that Option 1 did not approach the 50 percent cost savings goal; Option 2 approached it, though it did not meet the goal, reducing operations costs by about 37 percent; and both Option 3 alternatives exceeded that goal—Option 3A reducing costs by 59 percent and Option 3B by 78 percent.

A number of observations were made regarding relative costs. One was the difficulty of reconciling cost estimates for operational systems, which are well understood, with those for new vehicles whose definition is still in the pre-PhaseA state.

Compounding that difficulty was an uncertainty in the amount of cost growth margin to include in the estimates, which, in existing systems, was felt to be largely governed by external factors rather than inherent growth due to inadequate definition or design errors. The teams questioned, therefore, whether the historical cost growth allowances using conventional NASA models are too conservative if new management schemes are to be adopted that might better be able to shield the program from external factors.

An additional observation is that the NASA cost models are designed to predict development costs and lack a rigorous process for predicting operations costs. Nevertheless, the estimates developed for the Access to Space Study were made with guidance from experienced costing teams using the best costing tools available.

## **Operability**

Enhancements in the operability of the three options were also assessed. Option 1 improved the Shuttle operability somewhat, but that of the companion expendable launch vehicles was unchanged. Thus, taken as a whole, the operability of Option 1 was not significantly improved over the present situation.

All the new vehicles of Options 2 and 3 had designs, infrastructure, and operations concepts specifically tailored for operability and robustness, and associated significant reductions in operations costs. However, Option 2 retained the Delta and Option 3A retained the Titan, and, thus, their overall operabilities were thus somewhat degraded. Therefore, Option 3B promised the best operability of the three options.

## Technical Risk

It is apparent that the technical risk will increase with adoption of new design vehicles, and even more so if new technology is utilized. Thus, the technical risks were assessed as low for Option 1, low for the new vehicles of Option 2 since their designs have been defined in detail under the Advanced Launch System and National Launch Systems programs, moderate for the HL-42 crew carrier vehicle of Option 2, and moderate to high for Option 3 due to the incorporation of new technology. Even though Option 3 incorporates new technology, its risk was felt to be manageable due to the 4 to 5 year technology maturation phase which would develop and demonstrate the needed technologies to at least a level 6 technology readiness level (proven in their operating environment).

## Cost Risk

The cost risk was principally due to the schedule impacts of technical uncertainties during development. It was felt to be low to moderate for Option 1, moderate for Option 2, and moderate to high for Options 3A and 3B, the latter driven largely by the presence of new developments and new technology.

There was also a recognition that while the options that had new vehicles incurred greater cost and schedule risk, this risk increased in proportion to the cost savings they would enable.

## Other Factors

In addition to the factors assessed above, there are a number of other distinguishing features of the options that should be considered in making an architectural selection.

The first of these is the total capability of the Space Shuttle which, in addition to providing launch and return of payloads, has a capability to capture and repair spacecraft, and is also a crewed orbital research and development facility with an orbital flight duration of at least 2 weeks. These capabilities would not be replicated if Options 2 or 3 were to be selected, as crewed orbital laboratory functions are to be assumed by the Space Station. However, if the Space Station is not available, for whatever reason, this factor could have an overriding importance.

Another such factor is the ability for the U.S. commercial launch industry to compete in the international satellite launch market. Option 1 does nothing to improve the current situation. Option 2 would achieve approximate parity with the projected prices of the Ariane IV and Ariane V, the most efficient of the foreign systems, only after a lengthy development period. Option 3, on the other hand, would lower launch costs so dramatically that U.S. industry could underprice all competitors. The U.S. would likely capture, and once again dominate, the international satellite launch market for a considerable period of time, utilizing these unique advanced technology vehicles.

Lastly, it was recognized that providing two different means for assured access to space for every important payload will be prohibitively expensive, no matter how desirable. One way out of this dilemma is to recognize that the world has changed and that the international space launch community now has the capability and reliability to function as a backup, for launching U.S. payloads in the case of extensive groundings of U.S. launch vehicles. Thus, while some payloads would have to be designed to be compatible with more than one launch vehicle, assured access to space may be attained by any of the options studied, without major additional investment, by proper agreements with other nations.

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# Observations and Conclusions

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Assessment of the characteristics, performance, and costs of the architectures recommended by the option teams led to a number of observations which, in turn, lead to the study conclusions. These are presented below.

## Cost Reductions and Safety Increases

The study determined that it is indeed possible to achieve the objectives of large reductions of operations costs and increases in reliability and crew safety at the same time in the same architecture. It did not appear that reasonable modifications to the Space Shuttle could achieve these objectives in a cost-effective manner, though a number of beneficial improvements to the Shuttle system were identified.

New vehicles were required in the architectures to attain these objectives. These vehicles could be constructed using either conventional or advanced technologies, with the conventional technology vehicles approaching the 50 percent desired minimum operations cost reduction (37 percent reduction), and the advanced technology vehicles greatly exceeding it (up to 78 percent operations cost reduction).

## Design, Development, Test, and Evaluation Budget

Both current technology and new technology vehicles achieved the targeted operating cost reductions only after sizable design, development, test, and evaluation budget investments. This budget investment was smaller, but immediate, for the Option 2 architecture using current technology new launch vehicles and carriers. Both of the Option 3 architectures required a larger design, development, test, and evaluation budget, but start of their development was delayed 4 to 5 years as a result of the necessity of maturing and demonstrating the required technologies. Thus, Option 3 is more consistent with projected near-term budget availability.

## Annual Operations Costs

The annual operations costs of the Option 3B architecture were the lowest of all, since the new vehicle replaced all the current generation launch vehicles which have large operations costs.

The achievement of these low operating costs was completely dependent on making large-scale changes in the way vehicles are designed, developed, managed, contracted for, and operated. It was concluded that associated designs must all be driven by operations, as well as by performance, and that resulting architectures must also entail the major changes in launch infrastructure and operations "culture" referred to as "new ways of doing business."

## Most Attractive Option

In view of the above, an architecture featuring a new advanced technology single-stage-to-orbit pure-rocket launch vehicle was recommended as the most attractive option. It has the greatest potential for reducing annual operations costs as well as life-cycle costs, it would develop important new technologies with dual-use in industry (such as composite vehicle structures for cars and airplanes), it would place the U.S. in an extremely advantageous position with respect to international competition, and would leapfrog the U.S. into a next-generation launch capability.

The preferred single-stage-to-orbit rocket alternative is that in which the vehicle is sized so as to accommodate all payloads in the mission model, so as to avoid the need to carry current Titan expendable launch vehicles in parallel. The lowest operations costs resulted from selecting this single-stage-to-orbit pure-rocket vehicle as the focal point of the new launch architecture.

The large development costs associated with this new vehicle would be put off for at least 5 years while the technology was being matured and demonstrated. This would allow at least that time period for measured consideration of the decision to start a new vehicle program.

On the other hand, delaying the decision of which vehicle architecture to select by 4 or 5 years but not funding a focused technology phase will achieve nothing, since the lack of a focused technology program during that period will not reduce the risks of developing an advanced technology vehicle. Therefore, the choices available in 4 to 5 years would be exactly the same as those we face today.

## Technology Maturation and Demonstration

The assessment that the best option is to develop a new, fully reusable, advanced technology single-stage-to-orbit rocket launch vehicle is absolutely dependent on maturing and demonstrating the required technologies before initiating development.

Though it is possible to start development right away and perform technology maturation and demonstration concurrently, such an approach carries with it greater technical, schedule, and cost risks. Further, it would immediately require large budgets, precluding the 4 to 5 years of relatively modest budgetary investment. However, once the required technologies are matured and demonstrated at the subsystem/system level in the pertinent environment, the perceived risk is much reduced and should be manageable.

The technologies that require maturation and demonstration include graphite-composite reusable primary structures, aluminum-lithium and graphite-composite reusable cryogenic propellant tanks, tripropellant or lox-hydrogen engines designed for robustness and operability, low-maintenance intergral or standoff thermal protection systems, autonomous flight control, vehicle health monitoring, and a number of operations-enhancing technologies.

These technologies must be demonstrated on the ground and through flights of an experimental rocket vehicle. Technologies that interact should be tested together, both on the ground and in the experimental vehicle. A second objective of an experimental vehicle would be to validate the vehicle design models that are used to predict the characteristics and performance of single-stage-to-orbit rocket vehicles.

## Technology Applicability

The current expendable launch vehicles and the Space Shuttle will have to be operated for at least another 10 to 15 years before new launch vehicles can be available. Improvements to the fleet vehicles that significantly improve their operability and possibly reduce their operating cost should continue to be considered for implementation.

The technology program for the single-stage-to-orbit rocket would result in the evolution of numerous capabilities and/or components/subsystems that could be directly applied to these current launch vehicle systems. These could improve the operability and, to some degree, the cost performance of the current generation expendable launch vehicle fleet and the Space Shuttle until such time as the new vehicles became available to be phased in. The decision to upgrade the current fleet can be incremental and independent from that to start the technology program.

The new technologies will generally support the development of any type of new generation launch vehicle, even if initiated further in the future. In addition, most of these technologies are highly beneficial in their own right for applications throughout the civilian and defense communities and the commercial marketplace.

## Space Shuttle

Even though improvements to the Space Shuttle were identified and new vehicle designs were conceived that potentially could improve its cost and safety, it was clear that the Space Shuttle remains the world's most reliable launcher and is safe to fly utilizing today's rigorous processes until a next generation system becomes available.

The cost savings reported by the Option 1 team did not consider management or contract infrastructure changes. These areas have the potential to offer additional cost reduction benefits; however, considerations such as these were beyond the scope of the Access to Space Study. Such studies may be appropriate and beneficial and, if so, should be undertaken by the Space Shuttle Program. It is recognized that the Space Shuttle Program has already emphasized operational efficiency improvements in its program.

Lastly, the Option 1 team recommended further studies of flyback, fully reusable liquid-fueled boosters for the Space Shuttle in order to increase safety and potentially reduce costs. These studies should be performed to further develop the possible benefits such a configuration might offer.

## National Aerospace Plane

The selection of the rocket single-stage-to-orbit over the air-breathing single-stage vehicle by the Option 3 team was done for significant cost, risk, and schedule considerations. The air-breather option was determined to have more difficult technology and, therefore, would be more costly and take longer to develop.

However, air-breathing launchers potentially offer a number of unique mission capabilities in which they may have an advantage. These include launch into orbits with lower inclination than the latitude of the launch site, performing synergetic plane changes in order to over fly a given Earth location on successive orbits, and flexibility to perform single-orbit data collection missions. In addition, their technology is applicable to future hypersonic aircraft, both for civilian and defense applications.

Thus it was concluded that the National Aerospace Plane enabling technology program should continue independently of any decision to proceed with development of a nearer-term low-Earth orbit launch system.

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# Recommendations

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The Access to Space Study makes a number of recommendations. These are summarized below.

1. Adopt the development of an advanced technology, fully reusable single-stage-to-orbit rocket vehicle as an Agency goal.
2. Pursue a technology maturation and demonstration program as a first phase of this activity.
  - The technologies developed should be aimed at a single-stage-to-orbit rocket using tripropellant propulsion and advanced structures and materials. This program would mature and demonstrate the technologies described in the Description of the Option Teams Analysis (Option 3) section and summarized in the Observations and Conclusions section.
  - A complementary experimental rocket vehicle technology demonstration flight program should be pursued in parallel with the technology development activity.
  - These activities should be paced so as to allow the earliest informed decision on development of a full-scale vehicle.
3. The technology, advanced development, and experimental vehicle programs should be coordinated with the Department of Defense.
4. The Space Shuttle and the current expendable launch vehicle programs should be continued. The most beneficial and cost-effective upgrades should be considered for incorporation into these vehicles until the new single-stage-to-orbit vehicle becomes available.
5. Although the focus of these recommendations is a technology maturation and demonstration program, additional studies should be conducted in parallel. They include system trade studies for the single-stage-to-orbit rocket vehicle configuration in order to guide the technology activities, and assessment of a flyback reusable liquid booster concept for the Space Shuttle.
6. The National Aero-Space Plane enabling technology program should be continued as a separate and distinct activity, as it contributes to future defense and civilian hypersonic aircraft programs, and it has potentially unique future mission applications.







